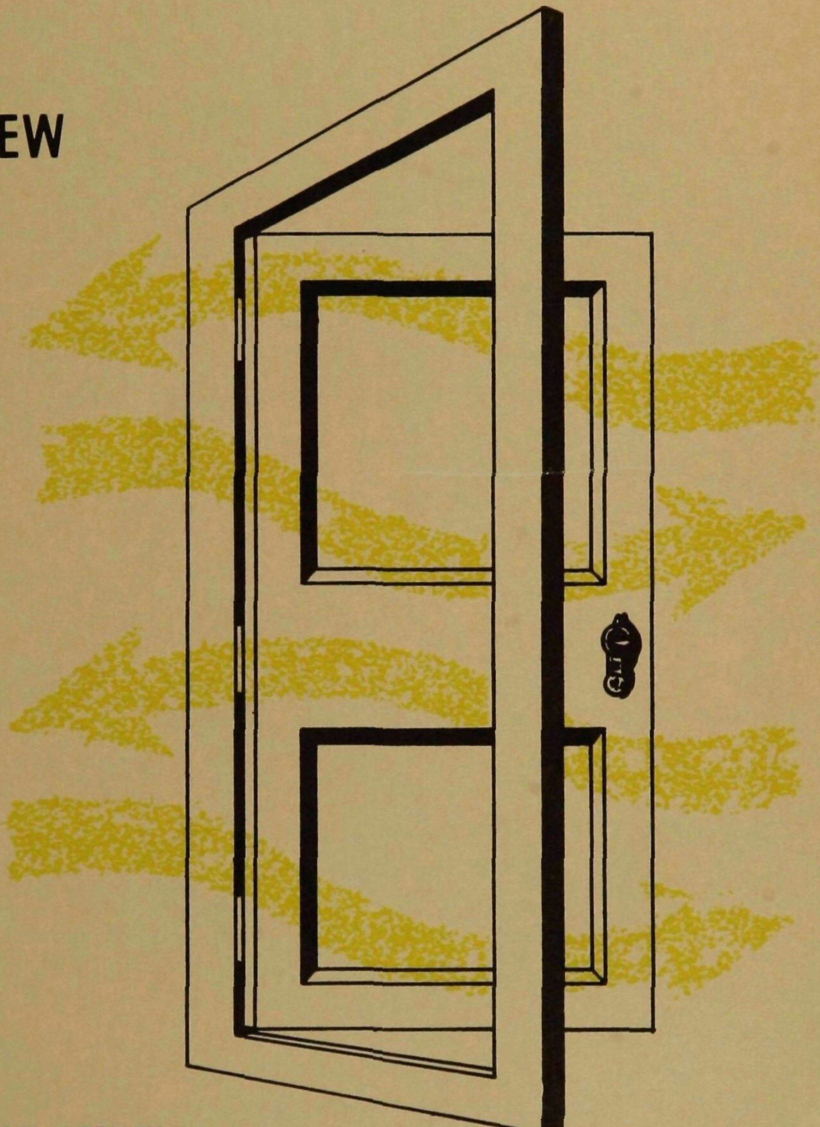
INDOOR-OUTDOOR AIR POLLUTION RELATIONSHIPS: A LITERATURE REVIEW



U.S. ENVIRONMENTAL PROTECTION AGENCY

INDOOR-OUTDOOR AIR POLLUTION RELATIONSHIPS: A LITERATURE REVIEW

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PREFACE

The information on which this report was based was compiled over a period of years by Mr. John J. Henderson, formerly of the Division of Health Effects Research but presently with the Regional Air Pollution Control Office, Dallas, Texas, and by Mr. Ferris B. Benson, Bioenvironmental Measurements Branch, Division of Health Effects Research, National Environmental Research Center (NERC), Research Triangle Park, North Carolina. Mr. D. E. Caldwell of the Technical Publications Branch, Information Services Division, Office of Administration, Research Triangle Park, North Carolina, organized and tabulated the data for further analysis and co-authored the review.

The authors wish to express their appreciation to Dr. R. J. M. Horton, Office of the Director, NERC, for his assistance in all aspects of the report preparation, but especially in locating pertinent information.

ABSTRACT

Extensive measurements have been and are being made of outdoor pollution. In contrast, very few data have been gathered on indoor pollution, especially in view of the importance of the problem. The data that are available are compiled and analyzed in this report. Based on a review of the literature, it was possible to infer relationships between indoor and outdoor pollution and to identify factors that affect these relationships. The relationships identified must be considered tentative, however, and further research is recommended to determine their validity.

Except for bacteria and, perhaps, for fungus spores, indoor pollution levels appear to be controlled primarily by outdoor concentrations. Other factors that influence indoor pollution levels include internal activities and pollutant generation, atmospheric conditions and natural ventilation, time, location, type of building, and air conditioning and filtration systems. At present, the best available estimate of indoor concentrations of particulates and nonreactive gases can be obtained by assuming them equal to outdoor concentrations. Indoor concentrations of pollen and reactive gases, expressed as a percentage of outdoor concentrations, decrease with increasing outdoor concentrations. Bacterial concentrations indoors appear to be more closely related to the presence and activities of people inside than to outdoor concentrations.

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INDOOR-OUTDOOR AIR POLLUTION RELATIONSHIPS: A LITERATURE REVIEW

CHAPTER 1. INTRODUCTION

Air pollution is defined in a number of air pollution control laws as" ...the presence in the outdoor atmosphere of one or more contaminants, or combinations thereof, in such quantities and of such duration as may be or tend to be injurious to human, plant, or animal life or property...." Thus, air pollution is legally defined in terms of outdoor concentrations. The average person, however, spends about 80 percent of his time indoors, and those who are most susceptible to the health effects of pollution, the elderly and the chronically ill, spend an even higher percentage indoors.[1]

Extensive measurements have been and are being made of the presence and concentrations of many types of pollutants in the outdoor air. In contrast, considering the importance of the problem, very few data have been gathered on the presence, concentration, and generation of pollutants in indoor environments and on the penetration of pollutants from the outdoor environment into buildings. Even though a large number of publications include some information of application to the problem of indoor pollution (over 75 publications are specifically cited in this report), only recently have comprehensive investigations of the problem been initiated.

It is the purpose of this report to compile the extant but scattered data and analyze them to determine if relationships can be established between indoor and outdoor pollution levels and to determine if other factors that influence indoor concentrations can be identified.

All information related to indoor-outdoor pollution relationships that could be located in published form was reviewed. Pollutant types considered included gases, particulates, and viable particles (pollen, fungus spores, and bacteria). Building types included residences, offices, laboratories, schools, hospitals, and public buildings. Buildings such as factories and manufacturing plants were considered to constitute a special problem beyond the scope of this study.

The review and analysis presented in the next chapters are highly dependent on the results of recently instigated studies in the United States[1-8] and on somewhat earlier studies in Japan.[9-14] Some of the data considered, however, were obtained as early as 1903. The data reviewed are not limited to United States publications. Significant contributions were culled from Japanese and Russian publications, and the literature of many other countries is represented.

The publications reviewed are described in an annotated bibliography prepared as a companion document to this report.[15] The bibliography also contains a number of references not specifically cited in this report. These include references that provided useful general background information for the review, but no specific information or data; foreign-language publications that were not translated for the review because of the constraints of time and money; and publications covering highly specific pollutants, such as biological warfare aerosols and radioactive particles, and buildings with special pollution problems, such as public garages.

All data of general application to indoor-outdoor pollution relationships are compiled and tabulated in Appendix A. These data are analyzed in the next chapter to determine possible general relationships between indoor and outdoor concentrations. In Chapter 3, factors other than outdoor concentrations that may affect the indoor-outdoor relationships defined in Chapter 2 are examined. In Chapter 4, the techniques that have been employed in measuring indoor pollution and the problems associated with such measurements are discussed. Chapter 5 includes a summary of the major conclusions resulting from this review and suggestions for further research to define and evaluate indoor-outdoor pollution relationships.

In the discussions that follow, indoor pollution levels are commonly expressed as a percentage of outdoor levels (indoor/outdoor concentrations x 100). The reader should keep in mind the fact that a low indoor/outdoor percentage does not necessarily imply a low indoor concentration. For example, in the relationship for sulfur dioxide presented in the next chapter, an interior concentration of 10 parts per hundred million (pphm) was found for an outside concentration of 15 pphm (indoor/outdoor = 67 percent). In another instance, the indoor concentration was 30 pphm when the outdoor concentration was 100 pphm (indoor/outdoor = 30 percent). Thus the actual indoor concentration at an indoor/outdoor ratio of 30 percent was much higher than at a ratio of 67 percent. This approach was employed to permit better definition of indoor pollution as a function of outdoor pollution. The identification of relationships between indoor and outdoor pollution would permit the estimation of indoor levels from the outdoor data, which are more abundant.

CHAPTER 2.

RELATIONSHIPS BETWEEN INDOOR AND OUTDOOR POLLUTION LEVELS

GASES

Data related to indoor concentrations of gaseous pollutants are presented in Tables A-1, A-2, and A-3.[2-4, 16-23] The data represent a wide range of studies conducted for varying purposes under a wide range of conditions. Except for sulfur dioxide (SO_2) and carbon monoxide (CO), the data are highly limited.

Sulfur Dioxide

Figure 2-1 presents the ratio between indoor and outdoor SO_2 concentrations (expressed as percentage) versus outdoor concentrations. With a few exceptions, the data follow a consistent pattern, as delineated in the figure. Indoor concentrations approach, or even exceed, outdoor concentrations when outdoor concentrations are low, but drop rather rapidly to about 50 percent of outdoor levels as outdoor concentrations increase up to about 20 pphm; then they drop more slowly to a value approaching 30 percent or less with further increases in outdoor levels. This relationship has been noted in several studies, in which, for the most part, indoor SO_2 concentrations have been found to be consistently lower than outdoor concentrations.[16, 21, 24-26]

Two factors affecting the lower concentrations of SO_2 indoors have been identified. First, SO_2 is reactive, and thus tends to be absorbed by walls and by interior surfaces and finishes.[3, 24] Second, outdoor peak concentrations, which are sharp and often of relatively short duration, are not fully reflected by indoor concentration patterns.[16]

Some reported data on indoor SO_2 concentrations were not included in Table A-1 and Figure 2-1 since mean values were not reported. These data generally support the relationship noted above, however. Weatherly[25, 26] reported an average indoor/outdoor ratio of 60 percent for outdoor concentrations ranging between 9.6 and 57.3 pphm for a laboratory in London. For another London laboratory,

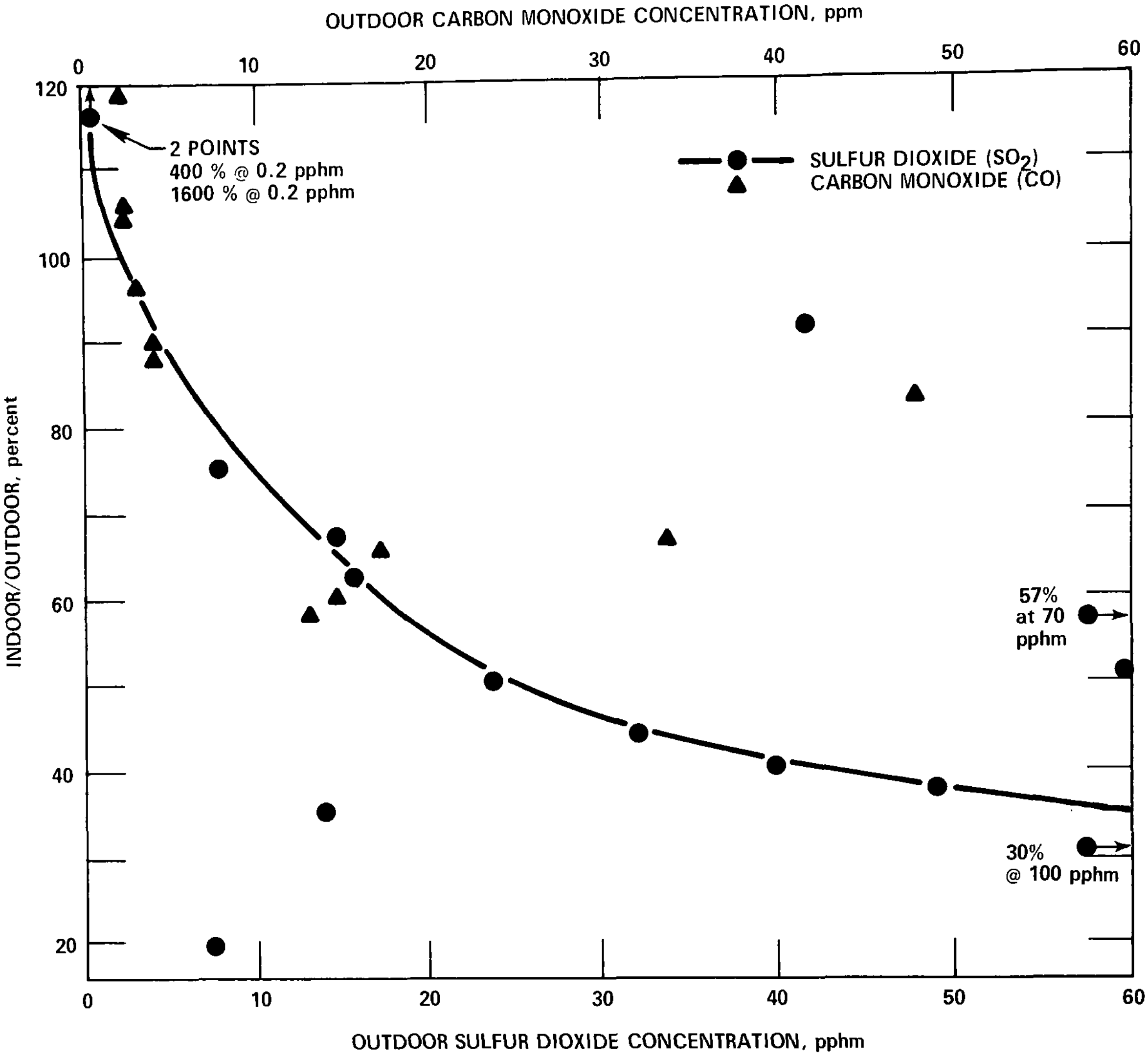

Figure 2-1. Indoor concentrations of sulfur dioxide and carbon monoxide as a function of outdoor concentrations.

Wilson[24] reported indoor/outdoor ratios ranging from 25 to less than 100 percent for indoor concentrations of 3 to 6 pphm and outdoor concentrations of 5 to 17 pphm.

A rather extensive program of SO_2 sampling was carried out in Boston and Cambridge, Massachusetts, by Arthur D. Little, Inc.,[8,9] but results were presented graphically, and average concentrations were not tabulated. (Raw data on an hourly basis are included in Reference 8.) For the low levels measured during the summer - generally between 3.5 and 5 pphm - indoor and outdoor levels were nearly equal. When outdoor concentrations rose above 5 pphm, indoor concentrations remained near their normal levels; but when outdoor concentrations fell below

3.5 pphm, indoor concentrations normally did also. For a period of several days in a building that housed both offices and laboratories, indoor concentrations were greater than outdoor concentrations. Outdoor concentrations were on the order of 4 pphm, however, and indoor levels were only about 5 pphm. For the higher SO_2 concentrations measured during the winter, the indoor-outdoor relationship was generally in accord with that shown in Figure 2-1, i.e., the difference between indoor and outdoor concentrations was greater when outdoor concentrations were higher.

Another rather extensive program of SO_2 sampling was conducted in Germany, but the results were reported only in general terms. These results indicated that indoor concentrations could be expected to range from 4 to 28 percent of outdoor levels for outdoor concentrations greater than 0.4 milligram per cubic meter (approximately 15 pphm), but that they might be as high as 80 to 100 percent if windows were open and a high wind was blowing.[27]

Carbon Monoxide

Carbon monoxide concentrations, also plotted in Figure 2-1, appear to follow a pattern similar to that shown for SO_2 concentrations. Based on the data plotted, it would appear that indoor CO concentrations range from 80 to greater than 100 percent for outdoor concentrations below 10 ppm, but range from 60 to 80 percent for outdoor concentrations above 10 ppm. These conclusions must be viewed with some suspicion, however. Carbon monoxide is unreactive, and indoor concentrations have been expected to approximate those outdoors after a certain lag time.[3,4] It should be noted also that the CO data shown in Figure 2-1 represent only two studies. All the data for outdoor concentrations below 10 ppm were obtained in Hartford, Connecticut,[2] and all data for concentrations above 10 ppm were obtained in Moscow.[22]

A limited amount of data in addition to that presented in Table A-2 and Figure 2-1 is available in the literature.[4,22,28,29] These data are representative of special conditions, however, and will be discussed later in the report in context.

Carbon Dioxide

As might be expected, data for carbon dioxide (CO_2) do not follow the same pattern as data for other gaseous pollutants. Except for emissions from smoking, cooking, and heating, the other pollutants are essentially produced outside, and indoor concentrations can be expected to be lower. Carbon dioxide, in contrast, is produced by people inside, and indoor concentrations can be expected to be higher. Assuming that outdoor concentrations are normally around 0.03 percent, concentrations in several types of office buildings were found to range from 1 to over 10 times outdoor levels (Table 2-1).[10] According to Ishido, a space of 10 cubic meters (m^3) per person and a recirculation rate of 30 m^3/hr are required to maintain CO_2 concentrations below 0.1 percent in rooms where people are doing office work.[10]

Table 2-1. INDOOR CONCENTRATIONS OF CARBON DIOXIDE FOR SEVERAL BUILDINGS IN OSAKA, JAPAN[10]

Type of building	Season	Indoor concentration range, percent
Office building	NS[a]	0.06 to 0.32
Old office building	Winter	0.08 to 0.28
Old office building	Summer	0.04 to 0.09
New air-conditioned office building	Winter	0.06 to 0.23
New air-conditioned office building	Summer	0.04 to 0.13
Newer air-conditioned building	NS	0.03 to 0.14

[a]NS not specified.

Summary

The data available for nitrogen dioxide, carbon bisulfide, hydrogen sulfide, and total gaseous acids (Table A-3) are insufficient for identifying relationships. From the data in Tables A-1 through A-3, and in Figure 2-1, however, it appears that indoor concentrations of gaseous pollutants are generally lower than outdoor concentrations, but by less than 50 percent unless outdoor concentrations are high. At very low levels of outdoor pollution, inside concentrations sometimes exceed outdoor concentrations. A definite trend of decreasing indoor/outdoor ratios with increasing outdoor concentration has been identified for SO_2 as shown in Figure 2-1. A similar trend for CO is a possibility, but, for the present, it seems wiser to assume that indoor CO levels will be equal to or only slightly less than outdoor levels. Concentrations of CO_2, since it is produced inside, are normally higher inside than out.

PARTICULATES

Data related to indoor concentrations of particulates are listed in Table A-4 and plotted in Figure 2-2.[2, 11-14, 18, 21, 25, 26, 29-39] Data for soiling index are

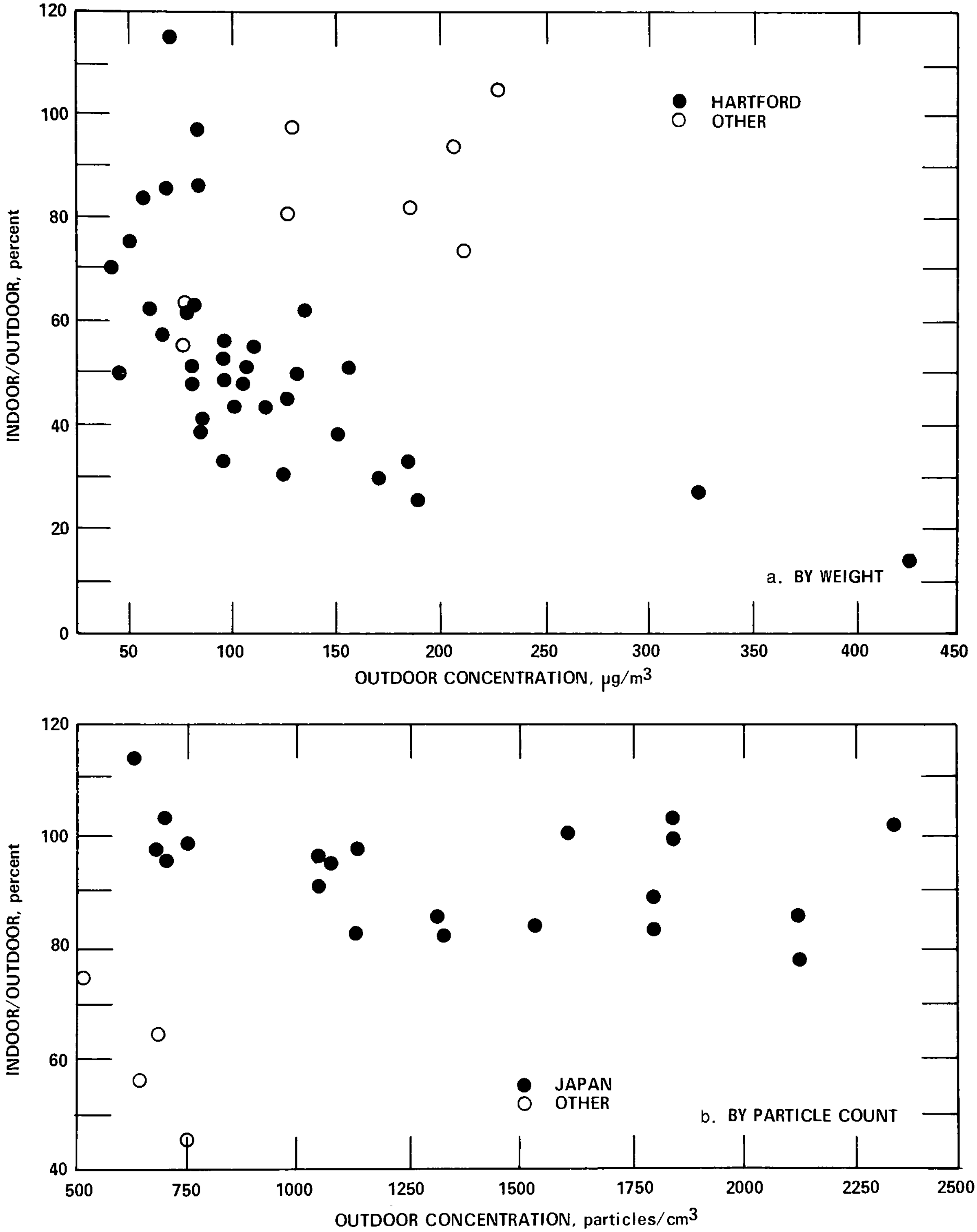

Figure 2-2. Indoor particulate concentrations as a function of outdoor concentrations.

not plotted because the majority of these data represent a narrow range of very low concentrations, and no patterns can be shown graphically.

The most obvious conclusions that might be drawn from Figure 2-2 are that indoor/outdoor particulate concentrations by weight generally decrease with increasing outdoor concentration, but that indoor/outdoor particle counts remain relatively constant at about 80 to 100 percent of outdoor concentrations regardless of outdoor concentration. These conclusions may well prove to be unfounded, however. Almost all the data for concentration by weight were obtained in one study conducted in Hartford, Connecticut,[2] and the data for particle counts, although based on several studies, were obtained primarily in Japan for the Department of Home Economics of Osaka City University.[11-14] In both cases, as can be seen in Figure 2-2, the trends noted above are not supported by the limited amount of data available from other sources.

Three possible trends in the relationship between indoor and outdoor particulate concentrations have been identified in the literature, as summarized, respectively, in the following three paragraphs. The first trend identified appears to be the best supported.

Ishido and his colleagues concluded, as a result of their studies in Japan, that, even in relatively air-tight buildings,[9] and in schools and hospitals as well as in small rooms,[11] indoor suspended particulate levels are completely under the influence of outdoor changes. They further concluded that the generation of dust by daily activities may have some effect, but that it is of relatively short duration and is not directly reflected in daily variations in indoor dust concentrations.[12-14] Although changes in indoor concentrations lag behind outdoor changes and the range of concentrations is smaller indoors, indoor levels are nearly equal to outdoor levels if mean values over 24-hour periods are considered.[9] These conclusions are supported by statistical analyses of the results of two studies[30, 32] which indicated that differences in indoor and outdoor concentrations were not significant at the 5 percent level. A study in Cincinnati indicated that "under normal atmospheric conditions, the main component of suspended matter in the home was drawn from outside air, while during 'smog' periods the correspondence of the two measurements was even closer."[34] A study in Rotterdam indicated that indoor/outdoor concentrations remained relatively constant at about 80 percent during 24-hour periods, regardless of outdoor concentrations.[21]

A study in a London office[25, 26] lends some support to the relationship indicated by Figure 2-2a, but not at the same concentrations or percentages. Indoor and outdoor concentrations were found to be about equal up to concentrations of 300 micrograms per cubic meter ($\mu g/m^3$). When outdoor concentrations were above this level, the concentrations indoors were less than those outdoors; and, the higher the outside concentrations, the greater the percentage difference. The lowest indoor/outdoor ratio noted, however, was 78 percent for an outdoor concentration of 800 $\mu g/m^3$. It has also been noted that indoor and outdoor levels showed fair agreement when windows were kept open, but that indoor levels were sometimes less than half of outdoor levels when windows were closed, particularly at night.[36]

Romagnoli, who concluded that indoor dust content does not seem to reflect the outside dust levels,[37] and Kanitz, who attached equal importance to outside concentrations and to the presence and activities of people inside,[40] must be considered in the minority. In some instances, however, such as in the crowded classrooms where Romagnoli obtained his data, the presence and activities of people inside may be of greater importance than outdoor concentrations.

The data in Figure 2-2 indicate a tendency for at least slightly lower particulate levels indoors. These data indicate indoor concentrations less than those outdoors in 42 of 44 instances (95 percent) by weight and 19 of 25 instances (76 percent) by particle count. In three studies that reported comparisons of this type for individual locations or sampling periods, ratios were 18 to 30 (60 percent),[30] 9 to 21 (43 percent),[31] and 16 to 24 (67 percent).[41] Thus, although indoor particulate concentrations are generally lower than outdoor concentrations, the pattern is not consistent, and a significant number of instances when indoor concentrations were higher than those outdoors have been reported.

There is some indication that the composition of indoor particles may differ from that of outdoor particles. In one study,[34] median particle diameter inside was found to be 0.36 micron, compared with 0.46 micron outside. In an air-conditioned office building, 99 percent of the particles were smaller than 0.7 micron, while 89 percent of outdoor particles were smaller than 0.7 micron.[42] In another study, 85 percent of indoor particles were found to be 1 micron or smaller, while only 74 percent of those outside were 1 micron or smaller.[32]

The difference in particle size in the latter study, however, was less than 0.2 micron and was not significant at the 5 percent level. In Hartford, the smaller particles associated with soiling index were found to penetrate buildings more readily than the larger particles associated with suspended particulate measurements.[2]

In still another study,[30] the ash content of the particles was determined. The ash content of indoor samples ranged from 1.5 to 38.0 percent, with a mean of 13.3 percent. Ash in outdoor samples ranged from 2.1 to 80 percent, with a mean of 29.3 percent. This difference, which was highly significant at the 1 percent level, indicates that indoor air contains more organic material than outdoor air. Higher organic contents for indoor particulates were also noted in the Hartford study.[2]

In summary, indoor particulate concentrations appear to be generally lower than outdoor concentrations, especially at high outdoor levels, and the composition of the particulates inside is different from that outside. As was the case for carbon monoxide, however, it seems best in light of the data presently available to assume indoor concentrations approximately equal to outside concentrations.

VIABLE PARTICLES

Not all particulate pollution is inanimate. Bacterial, fungal, and plant spores (including pollen), though "naturally," endogenously generated, are considered to be pollutants from a health effects standpoint (mold and pollen allergies), for purposes of indoor air quality control (air conditioning), when present in inordinate amounts, or when present because of human activity.

Spores

Indoor and outdoor concentrations of total fungal spores are presented in Table A-5.[43-58] Of the 21 indoor/outdoor ratios tabulated, 3 are noted to be exceptionally low (data for houses in Cardiff, Wales),[57] and 3 to be exceptionally high (data from Spain[51] and data from Sweden[49] for homes with poor hygienic conditions). Fourteen of the remaining 15 are below 90 percent. Consideration of those values below 90 percent indicates that averages are around 40 percent (mean 41 percent; median 38 percent; mode 30 to 40 percent). Thus it appears that indoor spore concentrations generally range from 15 to 90 percent and average around 40 percent of outdoor concentrations.

The wide disparities among measuring and reporting procedures in the studies summarized in Table A-5 preclude analysis of indoor/outdoor ratios as a function of varying outdoor concentrations.

Consideration of the composition of the spores found indoors and outdoors indicates that indoor populations are not directly controlled by outdoor populations. Indoor and outdoor concentration ratios of the ten most commonly reported types of spores are summarized in Tables 2-2 and 2-3. Detailed data on which

Table 2-2. INDOOR/OUTDOOR CONCENTRATION RATIOS FOR SPORES OF THE TEN MOST COMMONLY OCCURRING FUNGI[a]

Fungus	Range of indoor/outdoor ratios, %	Studies in which ratio reported was: <100 %	Studies in which ratio reported was: >100 %	Total studies
Penicillium	29 to 567	4	4	8
Cladosporium	0.3 to 26	7	0	7
Aspergillus	24 to 138[b]	4	2	6
Hormodendron	18 to 20	2	0	2
Mycelia sterilia[c]	24 to 30	2	0	2
Mucor	90 to 300[d]	1	4	5
Pullularia	4 to 50	4	0	4
Yeasts	27	1	0	1
Alternaria	0 to 44	6	0	6
Phoma	3 to 75	4	0	4

[a]Data from Spain[51] excluded since indoor/outdoor ratios were much higher than general data trend.

[b]Range does not include an instance in which Aspergillus was found indoors but not outdoors; ratio would approach infinity.

[c]The majority of these organisms are in the family Deutromycetes.

[d]Range does not include two instances in which Mucor was found indoors but not outdoors; ratio would approach infinity.

these summaries are based are presented in Tables A-6 to A-9. Table 2-2 compares the spores in terms of indoor/outdoor percentage and Table 2-3 in terms of percentage of total colonies. It should be kept in mind that the data in Table 2-3 do not allow direct comparisons between indoor and outdoor concentrations; rather, the data indicate the relative distribution of each type of spore in the total population, either indoors or out. These tables indicate that the spore composition of inside air samples is quite different from that of outside samples.

Penicillium is the most common spore found both indoors and out. Indoor concentrations have been reported to be significantly less than those outdoors (29

Table 2-3. DISTRIBUTION IN INDOOR AND OUTDOOR AIR OF SPORES OF THE TEN MOST COMMONLY OCCURING FUNGI

Fungus	Distribution in samples analyzed, percent		Locations (Total = 10)		Relative magnitude of indoor and outdoor percent of total colonies	Remarks
	Indoor	Outdoor	Indoor	Outdoor		
Penicillium	15.1 to 73.3	60 to 69.0	10	10	Indoors > outdoors in 9 of 10 cases	Found both indoors and outdoors at all locations
Cladosporium	15.8 to 35.9	37.2 to 69.0	6	6	Outdoors > indoors in all cases reported	
Aspergillus	0.4 to 28.6	0 to 23.2	10	8	Indoors > outdoors in 8 of the 10 cases	Present indoors, absent outdoors in 1 case
Hormodendron	12 to 28	44.0 to 68	3	3	Outdoors >> indoors in all 3 cases	
Mycelia sterilia	0.1 to 27.1	0.6 to 17.5	4	4	Outdoors > indoors in 3 of 4 cases	
Mucor	0.6 to 15.6	0 to 1.0	9	5	Indoors > outdoors in 8 of 9 cases	Present indoors, absent outdoors in 2 cases
Pullularia	1.9 to 10	5.7 to 18	5	5	Outdoors > indoors in all 5 cases	
Yeasts	7.3 to 13.2	3.6 to 17.6	4	4	Outdoors > indoors in 3 of 4 cases	
Alternaria	0 to 2.1	0.6 to 7.5	6	8	Outdoors > indoors in 8 of 9 cases	Present indoors, absent outdoors in 2 cases; reverse in 1.
Phoma	0.3 to 1.1	0.5 to 2.9	4	4	Outdoors > indoors in 3 of 4 cases	

to 76 percent) in half the studies and significantly greater (172 to 567 percent) in the other half. Considering indoor and outdoor populations separately, Penicillium generally constitutes a higher percentage of indoor fungus populations than of outdoor populations (Table 2-3).

Aspergillus is the next most common spore found, especially indoors. Although concentrations are generally lower indoors than out, Aspergillus is generally a more commonly occurring member of the indoor population. In at least one of the ten studies reported, Aspergillus was found to be present indoors but absent outdoors.

Cladosporium, while not occurring as frequently as Aspergillus, often constitutes a higher percentage of the population, especially outdoors, in those cases where it has been identified. Indoor/outdoor ratios are quite low, ranging from 0.3 to 26 percent, and Cladosporium is invariable a more important member of the outdoor population than of the indoor population, though it has been reported in one case to constitute over one-third of the spores inside.[54]

Hormodendron is also often an important component of indoor spore populations, but like Caldosporium, and to an even more marked degree, it is more prevalent in outdoor populations than indoor populations and indoor/outdoor ratios are uniformly low (12 to 28 percent). Mycelia sterilia shows similar trends, though not so marked, and the indoor/outdoor ratios are slightly higher (24 to 30 percent).

Mucor is the only one of the ten most common spores that consistently yields indoor/outdoor ratios greater than 100 percent. It is also more prevalent in indoor samples than in outdoor samples.

The remaining four commonly found spores constitute a higher percentage of the outdoor population than the indoor population in most instances. Indoor/outdoor ratios, however, tend to be somewhat higher than those for the molds previously discussed.

In summary, Penicillium, Aspergillus, and Mucor constitute a higher percentage of indoor samples than of outdoor samples. The remaining seven of the ten most commonly found fungus spores are more prevalent in outdoor samples. Except for these three fungi, examination of Tables 2-2 and A-6 indicates that indoor/outdoor ratios of spores are generally below the average (40 percent) indicated for total spores. The same holds true for the less common fungi listed in Table A-6, except for Oospora, Monilia, Rhizopus, and Aleurisma.

Although a few exceptions can be found in Tables A-6 through A-9 the same spores are normally found indoors and outdoors. Several investigators have concluded from this fact and from the assumption that relatively few spores are produced inside and released into the air that the most important source of airborne spores in normal clean, dry houses is the outside air.[53,54] However, differences in spore distribution in air samples indicate that indoor concentrations are not simply and directly related to outdoor concentrations. It is possible that different spores are transported indoors at different rates, but it is also possible that the growth and multiplication of these spores inside (especially those of Penicillium and Mucor) have a greater influence than has been assumed.

A limited amount of data is available on spore populations in house dust (Table 2-4), as opposed to airborne spores, which are discussed above. In the two locations studied, fewer genera of fungi were found in house dust than in air. The samples were made up exclusively of five of the most commonly found spores, and Penicillium was by far the most predominant genus. Aspergillus and Mucor were more abundant in dust than in either indoor or outdoor air in Spain.[51]

Table 2-4. COMPOSITION OF SPORE COLONIES IN HOUSE DUST

Fungus	Percentage of total colonies			
	Lexington, Kentucky[51]		Spain[52]	
	Summer	Winter	Madrid	Coast
Penicillium	48.7	49.6	87.1	84.4
Cladosporium	0	0	3.3	4.7
Aspergillus	35.2	35.9	3.9	2.6
Mucor	0	0	3.8	7.9
Alternaria	16.1	14.5	1.9	0.4
Other genera	0	0	0	0

Aspergillus was also found to be more abundant in house dust than in indoor or outdoor air in Kentucky.[52]

Pollen

Indoor and outdoor pollen concentrations are presented in Table A-10.[43,57,59-65] Most data on pollen concentrations have been gathered as part of evaluations of air conditioners and will be discussed in Chapter 3.

The data for non-air-conditioned buildings from Table A-8 are plotted in Figure 2-3 in terms of outdoor concentration versus indoor/outdoor ratio. The four data points for which outdoor concentrations were greater than 100 grains/m^3 were excluded to allow plotting on a more convenient scale. To facilitate comparison between concentrations in grains per cubic meter and number per sample, the medians were plotted coincident with each other.

A pattern of decreasing indoor/outdoor ratios with increasing outdoor concentration is indicated by the data bands in the figure. Consideration of data above 50 grains/m^3 in the figure and above 100 grains/m^3 in Table A-8 shows that the relation is probably not linear above about 50 grains/m^3, but is asymptotic, approaching a limit between 1 and 5 percent for outdoor concentrations above 100 grains/m^3. Thus it appears that indoor concentrations will vary from 85 to 100 percent of outdoor concentrations for low levels to 1 to 20 percent at high levels.

Bacteria

Data related to indoor and outdoor concentrations of bacteria are presented in Table A-11.[12,14,43,66] Indoor/outdoor ratios obtained for the house in Osaka,

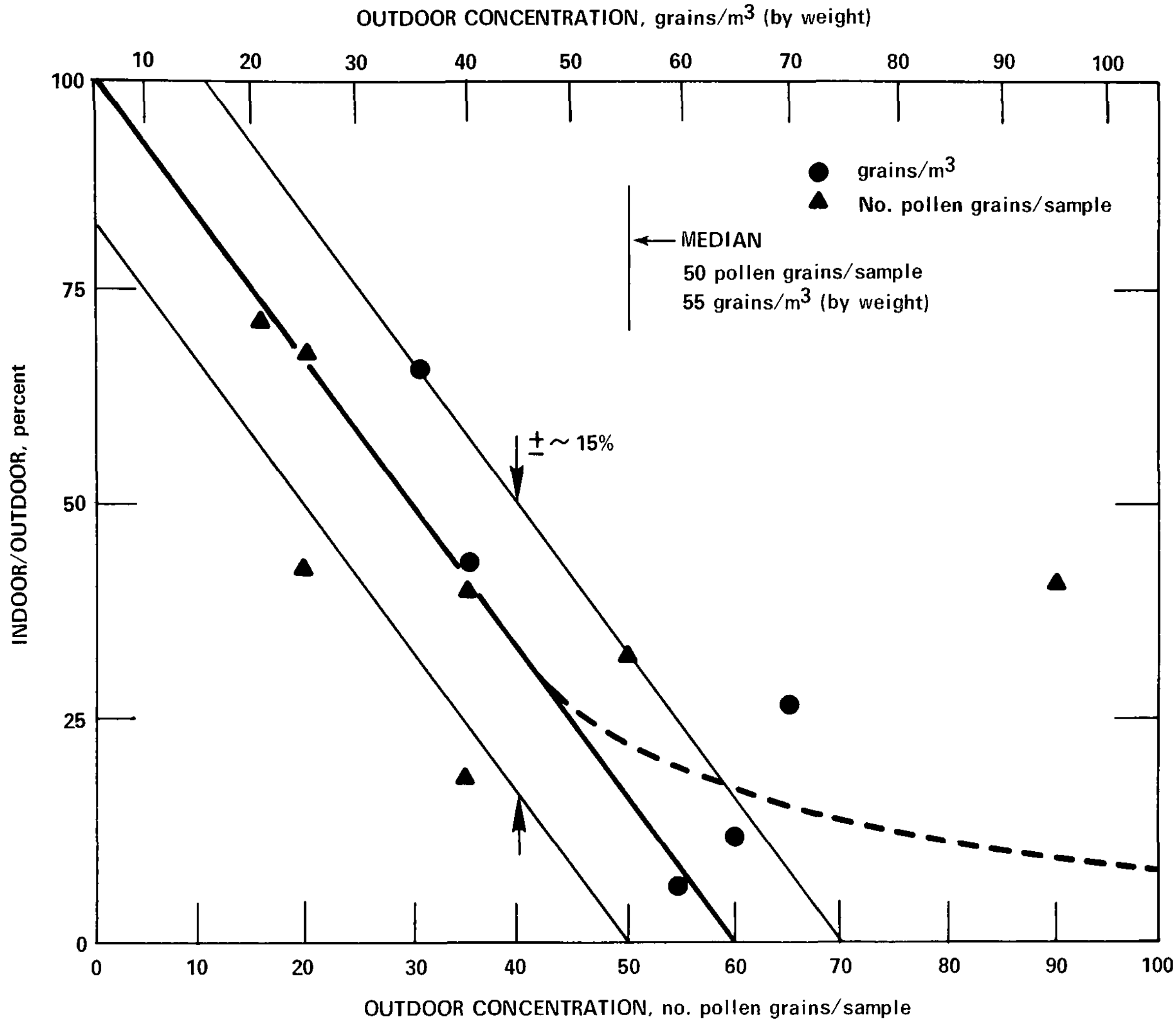

Figure 2-3. Indoor pollen concentrations as a function of outdoor concentrations, non-air-conditioned buildings.

Japan, are exceptionally high compared to the other data, and these values have been excluded in the following analysis. The remaining indoor/outdoor ratios in the table range from 62 to 273 percent, and half of the ratios are greater than 100 percent. A great disparity is noted between data obtained in Japan and in the United States, however, perhaps because the Japanese data are for total bacteria while most of the U.S. data are for streptococci and total "microbes" (which includes spores as well as bacteria). Indoor/outdoor ratios based on the Japanese data range from 62 to 225 percent, and only 38 percent of the values are greater than 100 percent. The range for the U.S. data is 75 to 273 percent, and 67 percent of the values are greater than 100 percent.

As with the data on spores, the disparities among measuring and reporting procedures preclude analysis of indoor/outdoor ratios as a function of varying outdoor concentrations. The consensus of the investigators, however, is that indoor bacterial counts do not reflect fluctuations in the outdoor air.[12, 14, 43] Dust density and bacterial counts indoors reportedly show different tendencies, but the data are insufficient for proving them unrelated.[14] The influence of living conditions and daily activities on changes in indoor bacterial count is considered relatively great.[12]

Summary

Available data on indoor pollen concentrations indicate a trend of decreasing indoor/outdoor ratios with increasing outdoor concentrations (Figure 2-3). Indoor bacterial concentrations do not appear to be directly related to outdoor concentrations. Several investigators have reported that the most important source of airborne spores in clean, dry houses is the outside air.[53, 54] Consideration of the composition of most indoor and outdoor spore populations does not support this hypothesis, however.

CHAPTER 3.
OTHER FACTORS AFFECTING INDOOR CONCENTRATIONS

INTERNAL ACTIVITIES AND POLLUTANT GENERATION

It has been a tacit assumption in the previous section, as in most of the publications consulted, that the primary source of interior pollution is the outside air. However, a number of sources of pollutants exist inside buildings, notably heating, cooking, and smoking. In addition, activities - such as sweeping and dusting, dress ing, and drying clothes - that entrain dust can affect interior concentrations of suspended particulate and airborne spores as well as the rate of diffusion of gaseous pollutants. In addition, the nature and types of interior furnishings and finishes can affect the rate of adsorption of reactive gases. These effects on interior pollutant concentrations are discussed below.

Gases

Sulfur Dioxide - Interior generation of SO_2 is probably limited to faulty heating systems burning oil or coal.[3] Biersteker et al. reported that indoor SO_2 concentrations were not generally affected to a significant extent by the heating method used. However, in one 30-year-old home presumed to have a faulty heater, indoor concentrations averaged 3.8 times the outdoor levels.[21] Table 3-1 shows a comparison of SO_2 concentrations for new and old coal-heated houses in Hartford. The exceptionally high indoor concentrations for the old coal-heated house are presumed to be caused by a faulty heating system. Indoor concentrations at this house were found to be unrelated to outdoor concentrations; peak values were related instead to the stoking periods of the furnace. Indoor concentrations at the new

Table 3-1. SULFUR DIOXIDE CONCENTRATIONS FOR TWO COAL-HEATED HOUSES[4]

Type of building	Concentration, pphm Indoor	Concentration, pphm Outdoor	Indoor/outdoor, %
New house	5	14	36
Old house	78	10	780

coal-heated house were much lower than at the old house, even though outdoor concentrations were slightly higher at the new house.[3,4]

Indoor SO_2 concentrations are reduced by adsorption. According to Chamberlain, walls and ceilings should provide a perfect sink for SO_2. Thus the rate of adsorption should be controlled by the rate of diffusion across the boundary layer to the surface, and vigorous circulation, which would decrease boundary-layer resistance, should cause increased reductions in SO_2 concentration.[67] Wilson found that removal of SO_2 from indoor air was limited by the properties of interior surfaces and only slightly by transport to the surfaces. The ceiling (fiberboard with eggshell paint) was found to be effective in removing SO_2. The floor (lacquered cork), walls (painted with emulsion paint), and treated wood surfaces were not. "Stirring" the air was found to reduce concentrations by 10 to 40 percent, with the most reduction effected at higher concentrations.[24]

Carbon Monoxide - Carbon monoxide is generated indoors by combustion (smoking, heating, cooking).[3] The effect of combustion can be seen in the data from Russia in Table 3-2. Indoor concentrations in the natural-gas-equipped home 100 meters from the plant were higher than those in a home without natural gas located closer to the plant.[22]

Table 3-2. CARBON MONOXIDE CONCENTRATIONS NEAR A PLANT WITH AN OPEN HEARTH FURNACE[22]

Distance from plant, meters	Concentration, ppm		Indoor/outdoor, %
	Indoor	Outdoor	
50	11.6	17.8	65
100	16.3	16.5	99
250	9.0	14.9	60
500	7.6	12.8	59

According to Yocum et al. (1971),[2] gas heating systems do not appear to affect indoor CO concentrations, but gas stoves and attached garages do. (It seems reasonable to assume that gas stoves and garages are also a significant source of indoor nitrogen dioxide, but no data were found from which the magnitude of this effect could be evaluated.) The effects of stoves and garages on indoor CO concentrations can be seen in Figure 3-1, which shows the CO concentrations in a house in Hartford having a gas range and an attached garage. The family room is between

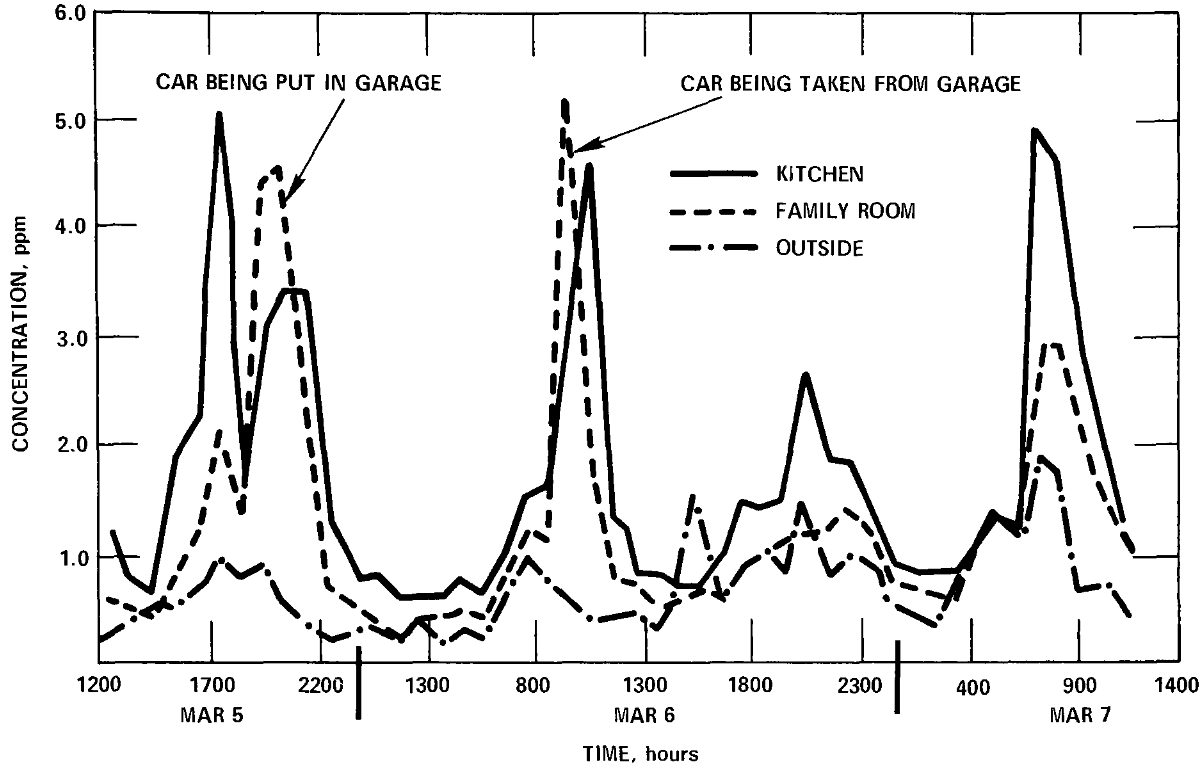

Figure 3-1. Carbon monoxide concentrations in house with gas range and furnace and with attached garage.[3]

the kitchen and the garage. For this house, CO concentrations are generally much higher than and unrelated to outdoor levels. Peak concentrations in the kitchen correspond to the periods when meals are being cooked, and concentrations in the family room generally follow those in the kitchen rather than those outside. For two periods in the record, when the car was being put into or taken out of the attached garage, the emissions from the garage are the controlling influence on both the family room and kitchen concentrations.[3]

Particulates

Particulates are also generated by combustion (heating, cooking, smoking).[3] Smoking has been found to significantly increase particulate concentrations indoors.[21, 68] According to Lefcoe and Inculet, smoking just one cigar raised particle counts by a factor of 10 to 100. Elevated counts persisted for a period of 1 to 3 hours.[68] Yocom et al. (1971)[2] note that the higher concentration of organic particles indoors may result in part from interior generation of pollutants from cooking or smoking, although the fact that smaller organic particles penetrate more readily than larger inorganic particles is also partly responsible for the difference.

Particles that are present inside are resuspended and/or kept in suspension by the activities of the people inside. Seisaburo et al.[14] reported particulate concentrations at different heights during waking and sleeping periods. These measurements (Table 3-3) indicate that particles are distributed rather uniformly from floor to ceiling because of activities of people during the day, but that during the night they tend to settle and become concentrated near the floor. Table 3-4 shows particle counts in Italian schools before, during, and after classes. Counts were much higher during classes than before in two of the four cases, presumably because of the presence and activities of the students.* There was also an increase in particle size from a mean of 0.5 micron before class to 1.2 microns during class. The measurements made after class indicate that concentrations do not drop rapidly after activities have ceased.[37] This conclusion is supported by the data of Lefcoe and Inculet, which indicate that high particle counts resulting from cleaning and dusting persist for a period of at least several hours.[68]

Table 3-3. INDOOR PARTICULATE DISTRIBUTION BY HEIGHT FOR WAKING AND SLEEPING PERIODS[14]

Height above floor, cm	Concentration, particles/cm^3	
	Waking hours	Sleeping hours
40	676	664
100	629	640
150	636	587
210	669	538

Table 3-4. PARTICLE COUNTS BEFORE, DURING, AND AFTER CLASSES IN SCHOOLS[37]

Location of school	Period		
	Before	During	After
Urban	348	347	410
Surburban residential	100	360	315
Surburban industrial	180	421	420
Rural	449	392	490

*Measurements were made at set times and do not necessarily indicate peak concentrations. Thus higher values measured after class in two instances do not indicate a continuing increase in concentration.

A number of investigators have concluded that indoor generation and entrainment of particles have a significant effect on indoor-outdoor relationships. In an office with an air filtration system that reduced interior concentrations to 24 percent of outside levels, the amount of dust generated in a room was found to be proportional to the number of people in the room.[42] An equation was developed for this relationship:

$$M=(0.72n + 1) \times 10^{-3}$$

where: m = the amount of dust generated, m^3/sec

n = number of people

Based on limited measurements for air-conditioned office buildings in Hartford, it was concluded that internal generation of suspended and soiling particulates was a significant factor in the estimation of interior concentrations. For these buildings, the ratio of internal generation to exterior concentration was estimated to range from 0 to 0.6 for indoor/outdoor ratios of 30 to 116 percent (the method of estimating these ratios is not specified).[6] Internal generation may also contribute to the varying indoor/outdoor ratios and to the indoor/outdoor ratios greater than 100 percent in the Hartford study.[2,6]

Viable Particles

As pointed out previously, indoor bacterial concentrations appear to be more closely related to indoor living conditions and activities than to outdoor concentrations.[12-14] Pollen, in contrast, is almost completely dependent on outdoor concentrations, as would be expected. As stated in Chapter 2, the importance of internal generation of spores is not clearly established. Maunsell found, however, that activities such as cleaning and dusting cause spores to be entrained in the air. The resulting increase in entrained spores was mainly in Penicillium, Cladosporium, Pullularia, and yeasts. Spores of larger sizes, which were absent in undisturbed air, were found to be present after dust was raised.[48]

Summary

The indoor generation of SO_2 is not normally an important consideration. Significant exceptions occur, however, when faulty oil- or coal-burning heating systems are encountered. Carbon monoxide is generated by smoking, cooking, and heating. Although gas furnaces or heaters are probably not significant sources of indoor CO, gas ranges apparently are. Attached garages are also a significant source.

Particulates can also be generated indoors from combustion (heating, cooking, smoking). Smoking, in particular, has been definitely identified as a significant source of particulates indoors. Interior generation may account for some of the scatter in particulate concentration data and may at least partially explain indoor/outdoor ratios greater than 100 percent. Indoor activities seem to enhance entrainment of particles already present indoors.

Indoor concentrations of bacteria appear to be highly dependent on indoor living conditions and activities, but pollen concentrations are almost completely dependent on outdoor concentrations. The importance of internal generation of spores is not clearly established, but, as with other particles, internal activities can play an important role in the entrainment of spores found indoors.

Sulfur dioxide (and probably other reactive gases as well) is removed from interior air by adsorption, the rate of which is dependent primarily on the properties of the interior surfaces and only slightly on the rate of transport to the surfaces.

ATMOSPHERIC CONDITIONS AND NATURAL VENTILATION

The importance of atmospheric conditions and natural ventilation was reconized in a study in Cincinnati that revealed large differences in domestic concentrations over short distances in the city, depending on window ventilation, on the proximity of buildings to pollution sources, on wind direction, and on thermal inversions.[35] The way in which these factors can interact to influence indoor-outdoor pollution relationships can be seen in the following example from the study in Hartford.[2,3]

Simultaneous CO samples were taken inside the dining room and on the outside of a house in Hartford. Sampling for 1 day is shown in Figure 3-2. On the evening illustrated, outside concentrations increased rather rapidly to about 12 ppm because of a light wind from a nearby interstate highway. Indoor concentrations remained around 5 ppm, about equal to the outdoor concentration before it increased. Because the windows and doors of the house were closed and there was relatively little influx of air, interior concentrations reacted much more slowly to

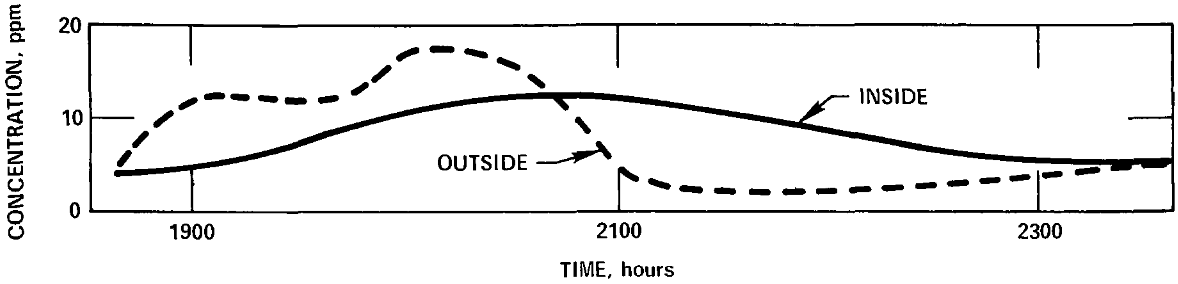

Figure 3-2. Carbon monoxide concentrations for house in Hartford, Connecticut; September 22, 1969.[2,3]

the change in wind direction than outdoor concentrations did. After 2 hours, outdoor concentrations had increased to about 16 ppm, but indoor concentrations were still significantly lower at 10 ppm. At this time, the wind direction changed, causing outside concentrations to drop rapidly to about 3 ppm. Inside concentrations remained high, however, and required 2.5 hours to return to the low outside ambient level. Thus, over a 5-hour period, indoor concentrations ranged from much lower to much higher than outdoor levels (indoor/outdoor ratios ranged from about 40 to more than 300 percent).[2,3] If either windows or doors had been even partially open or if a stronger wind had been blowing directly at the windows, resulting in greater natural ventilation, interior concentrations would probably have more nearly reflected those outdoors.[27]

As mentioned, several studies conducted in Japan have led to the conclusion that indoor particulate concentrations are not affected by natural ventilation but are controlled entirely by outside concentrations.[9-14] Other investigators, however, have noted a significant effect from natural ventilation. Studies in Cincinnati indicated that indoor and outdoor levels were in fair agreement when windows were open but that indoor concentrations were sometimes less than half of outdoor concentrations when windows were closed. Average indoor concentrations were found to be roughly 15 percent higher with windows open than with windows closed.[36] Results of the Hartford study mentioned above also support the contention that natural ventilation affects indoor particulate levels. A seasonal decrease was noted in the indoor/outdoor percentage from summer to winter, and was hypothesized to be the result of shutting up buildings for the winter.[2] It was also noted that particulate levels were lower in public buildings than in homes, which can be explained by a lower air infiltration per volume for the public buildings.[3]

Indoor pollen concentrations were found to be closely associated with both wind speed and window opening.[62] When windows were closed, indoor/outdoor ratios remained relatively constant at approximately 20 percent for wind speeds up to 8 miles per hour (mph). For higher wind speeds, there was a nearly linear increase in indoor/outdoor ratios up to 97 percent at 15 mph. When windows were open, penetration of pollen was quite different, but the amount of opening apparently made little difference.

TIME

Figure 3-2 and the related discussion show how inside concentrations and the relation between indoor and outdoor concentrations can vary with time. Indoor and outdoor concentrations of nonviable and viable particles, as well as of gases, have been found to vary on diurnal and seasonal bases, and the relationship between indoor and outdoor concentrations has also been found to vary in some cases. The time-related variations in indoor pollution levels that can be inferred from the literature are discussed in the following sections.

Gases

Simultaneous study of atmospheric and indoor air for 24 hours for Russian homes in the vicinity of a plant with a blast furnace showed parallel changes in CO concentrations, as indicated in Table 3-5.[22] Similar diurnal patterns for carbon monoxide have been reported for American homes, that is, high concentrations in the late night and early morning hours, low concentrations later in the morning (between 7 a.m. and noon), and high concentrations in the afternoon and evening.[2,3] The fact that the higher indoor/outdoor ratios correspond to the higher outdoor concentrations seems surprising at first, but this may result from a difference in

Table 3-5. VARIATION OF CARBON MONOXIDE CONCENTRATIONS WITH TIME NEAR PLANT WITH BLAST FURNACE[22]

Time, hr	Concentration, ppm		Indoor/outdoor, %
	Indoor	Outdoor	
0600	21.8	21.8	100
1000	3.1	6.2	50
1400	18.7	28.0	67
1800	9.3	21.8	43
2300	24.9	24.9	100

response time between indoor and outdoor levels as noted in the instance shown in Figure 3-2. The data do illustrate, however, that the indoor-outdoor relationship varies with time.

Day and night concentrations of carbon monoxide inside and outside a number of buildings were measured in Hartford, Connecticut, during the summer, fall, and winter (Table A-2).[2] To better illustrate the diurnal patterns indicated by these data, ratios of the concentrations during the day to those during the night are given in Table 3-6.

Table 3-6. DAY/NIGHT RATIOS OF CARBON MONOXIDE CONCENTRATIONS, HARTFORD, CONNECTICUT[2]

	Day/night ratio					
	Summer		Fall		Winter	
Building	Inside	Outside	Inside	Outside	Inside	Outside
Library	1.49	1.72	1.05	1.30	1.72	2.09
City Hall	1.52	1.72	1.14	1.30	1.74	2.02
100 CP	1.18	0.91	1.44	1.36	1.18	1.26
250 CP	1.07	1.05	1.25	1.38	0.97	1.76
Blinn St.	0.76	0.80	0.91	0.95	0.98	0.98
Carroll Rd.	0.78	0.76	1.09	1.23	0.93	0.92

The day/night ratios indicate that concentrations both inside and outside are higher during the day, except at the Blinn Street home for all three seasons and at the Carroll Road home during the summer and winter. The day/night ratios are lower indoors than out; that is, there is less difference between day and night concentrations indoors than out. Notable exceptions to this trend occur at the office buildings at 100 Constitution Plaza (CP). A seasonal effect on the diurnal pattern can also be inferred from the data in Table 3-6. In almost all cases, there is less difference between day and night concentrations in the summer than in the winter.

Indoor/outdoor ratios from the Hartford study are listed on day/night and seasonal bases in Table 3-7. With few exceptions, the ratios are lower during the day, corresponding to the higher concentrations noted above. Again, the notable exceptions to this trend are the data for summer and fall at 100 CP, for which concentrations were lower and indoor/outdoor ratios were higher during the day.

Table 3-7. INDOOR/OUTDOOR PERCENTAGES OF CARBON MONOXIDE, BY DAY AND NIGHT, HARTFORD, CONNECTICUT[2]

	Indoor/outdoor, %						Day/night ratio for indoor/outdoor %		
	Summer		Fall		Winter				
Building	Day	Night	Day	Night	Day	Night	Summer	Fall	Winter
Library	87	100	78	96	84	101	0.87	0.81	0.83
City Hall	89	102	89	101	80	93	0.87	0.88	0.86
100 CP	131	100	132	125	113	121	1.31	1.05	1.07
250 CP	105	102	96	104	76	96	1.03	0.92	0.79
Blinn St.	102	107	103	108	107	108	0.96	0.96	0.99
Carroll Rd.	104	102	96	108	112	112	1.02	0.89	1.00

A definite time lag has been noted between indoor and outdoor changes in concentrations of CO, as can be seen in Figure 3-2. In the instance shown, which represents a relatively tight house with doors and windows shut, the lag time amounted to 2.5 hours, and indoor concentrations exceeded outdoor concentrations during that period. Measurements of indoor and outdoor concentrations of total gaseous acid have indicated lag times of up to 2 hours.[16]

Particulates

Figure 3-3 shows the diurnal pattern obtained during the summer for a Japanese apartment.[14] The pattern should be fairly typical for the Japanese studies because similar patterns were found throughout the year and indoor and outdoor patterns were generally found to be almost identical.[12-14] The pattern may also be grossly applicable to the United States. It has been noted that daytime levels are higher than night levels,[5] and the major peak at around 8 a.m. has been identified.[18,36]

A slight lag time can be seen for the indoor concentrations in Figure 3-3, and it is reported that the lag time at night is even more apparent during the winter.[14] The effect of the lag time in the example illustrated is relatively minor, but it does result in indoor levels higher than outdoor levels twice during the period covered - "at about 1800 hours and from 2300 to 0100 hours." Lag times, sometimes amounting to an hour or more, have been reported in other instances, and indoor curves may show fewer sharp peaks than outdoor curves.[9,36]

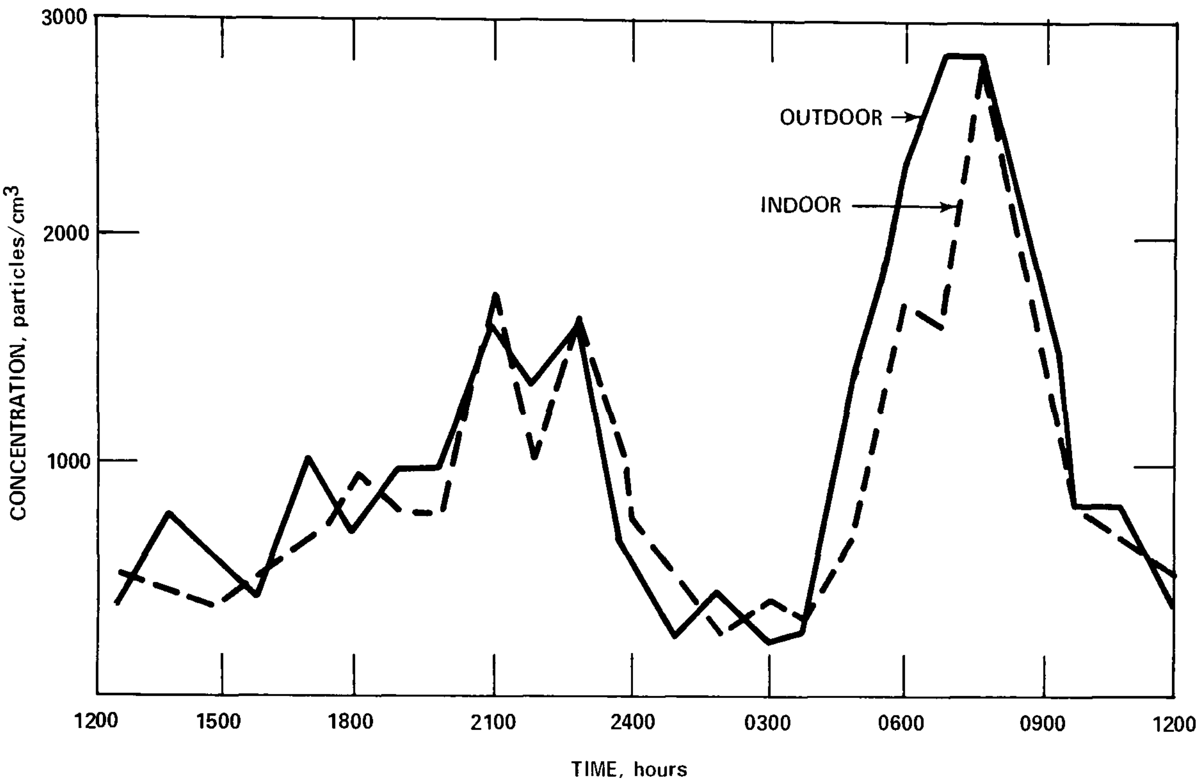

Figure 3-3. Concentration of particles in an apartment in Toyonaka City, Japan, May 21-22, 1956.[14]

Measurements of daytime and nighttime particulate concentrations, similar to those presented above for carbon monoxide, were also taken as part of the Hartford study, and the resulting day/night ratios are listed in Table 3-8.[2] Day/night ratios are greater than 1 except for two values that are nearly equal to 1. These values indicate that daytime concentrations of particulates are higher than nighttime levels by as much as 100 percent. For the offices and public buildings, indoor day/night ratios are lower than outdoor day/night ratios in the summer and

Table 3-8. DAY/NIGHT RATIOS OF PARTICULATE CONCENTRATIONS, HARTFORD, CONNECTICUT[2]

	Day/night ratio					
	Summer		Fall		Winter	
Building	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Library	1.53	1.61	1.30	1.50	1.49	2.24
City Hall	1.59	1.96	1.64	1.41	1.70	1.94
100 CP	1.09	1.12	1.33	1.26	0.98	1.53
250 CP	0.94	1.14	1.65	1.43	1.87	1.89
Blinn St.	1.25	1.21	1.20	1.29	1.40	1.33
Carroll Rd.	1.62	1.13	2.00	1.28	1.60	1.21

winter, indicating that there is less difference between day and night concentrations inside than out. For the houses, there is a greater difference between daytime and nighttime concentration inside than outside except, perhaps, during the fall. The ratios generally increase from summer to winter, indicating that there is more variation in concentrations, both inside and outside, in the winter than in the fall and more variation in the fall than in the summer.

Indoor/outdoor percentages for the Hartford study are listed on day/night and seasonal bases in Table 3-9. For the offices and public buildings, the percentages are slightly less during the day in summer and winter, reflecting the higher daytime concentrations noted above. For one of the houses, day and night percentages were nearly equal throughout the year; for the other, daytime percentages were much higher than nighttime percentages.

Table 3-9. DAY/NIGHT RATIOS OF INDOOR/OUTDOOR PERCENTAGES FOR PARTICULATE CONCENTRATIONS, HARTFORD, CONNECTICUT[2]

	Indoor/outdoor, %						Day/night ratio for indoor/outdoor %		
	Summer		Fall		Winter				
Building	Day	Night	Day	Night	Day	Night	Summer	Fall	Winter
Library	50	52	38	44	16	26	0.96	0.86	0.62
City Hall	51	63	62	53	27	30	0.81	1.17	0.90
100 CP	48	49	75	71	31	48	0.96	1.05	0.64
250 CP	45	55	58	50	33	33	0.82	1.16	1.00
Blinn St.	87	86	56	61	43	41	1.01	0.92	1.05
Carroll Rd.	115	84	97	62	51	39	1.37	1.56	1.30

Considering soiling particulate values in Tables 3-10 and 3-11, as opposed to the suspended particulate data in Tables 3-8 and 3-9, daytime and nighttime levels appear to be roughly the same, with no consistent differences between the two values. This difference in behavior between suspended and soiling particulates is probably the result of size differences; the smaller soiling particles tend to stay suspended at night whereas the larger particles contributing to the daytime suspended particulate measurement tend to settle out at night.[2]

Indoor and outdoor particulate concentrations were determined on a seasonal basis in two Japanese studies[12,14] and in the Hartford study mentioned above.[2] Results of the Japanese studies are summarized in Table 3-12. The data indicate

Table 3-10. DAY/NIGHT RATIOS OF SOILING PARTICULATE CONCENTRATIONS, HARTFORD, CONNECTICUT[2]

Building	Day/night ratio					
	Summer		Fall		Winter	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Library	1.36	1.35	1.03	1.12	1.21	1.18
City Hall	1.33	1.37	1.15	1.14	1.20	1.18
100 CP	0.87	0.84	1.00	1.12	1.03	1.08
250 CP	0.81	0.89	1.05	1.12	1.20	1.12
Blinn St.	0.87	0.83	0.97	0.94	0.89	0.80
Carroll Rd.	0.91	0.84	1.08	0.95	0.90	0.81

Table 3-11. DAY/NIGHT RATIOS OF INDOOR/OUTDOOR PERCENTAGES FOR SOILING PARTICULATE CONCENTRATIONS, HARTFORD, CONNECTICUT[2]

Building	Indoor/outdoor, %						Day/night ratio for indoor/outdoor %		
	Summer		Fall		Winter				
	Day	Night	Day	Night	Day	Night	Summer	Fall	Winter
Library	81	81	92	94	50	49	1.00	0.98	1.02
City Hall	98	100	115	114	94	93	0.98	1.01	1.01
100 CP	87	83	69	79	85	89	1.05	0.87	0.96
250 CP	57	62	79	84	58	55	0.92	0.94	1.05
Blinn St.	89	85	88	89	82	74	1.05	0.99	1.10
Carroll Rd.	119	110	80	67	93	83	1.08	1.19	1.12

Table 3-12. DUST DENSITIES FOR WINTER, SPRING, AND SUMMER, JAPAN[12,14] (Particles/cm^3)

Location	November			March			May			June		
	Indoor	Outdoor	Indoor/outdoor, %	Indoor	Outdoor	Indoor/outdoor, %	Indoor	Outdoor	Indoor/outdoor, %	Indoor	Outdoor	Indoor/outdoor, %
Osaka		1,897		1,287	1,528	84	978	1,047	91	738	752	98
Toyonaka												
Living room	1,839	2,133	86	1,602	1,801	89	931	1,129	82	670	703	95
Bedroom	1,654	2,133	78	1,497	1,801	83	1,091	1,129	96	726	703	103

a fairly regular decrease in indoor and outdoor concentrations and a corresponding increase in indoor/outdoor ratio from winter to summer.

Some seasonal trends indicated by the Hartford data have been identified above as they relate to diurnal patterns. The seasonal variation in concentration and indoor/outdoor ratio can be seen in Figure 3-4, which shows the area

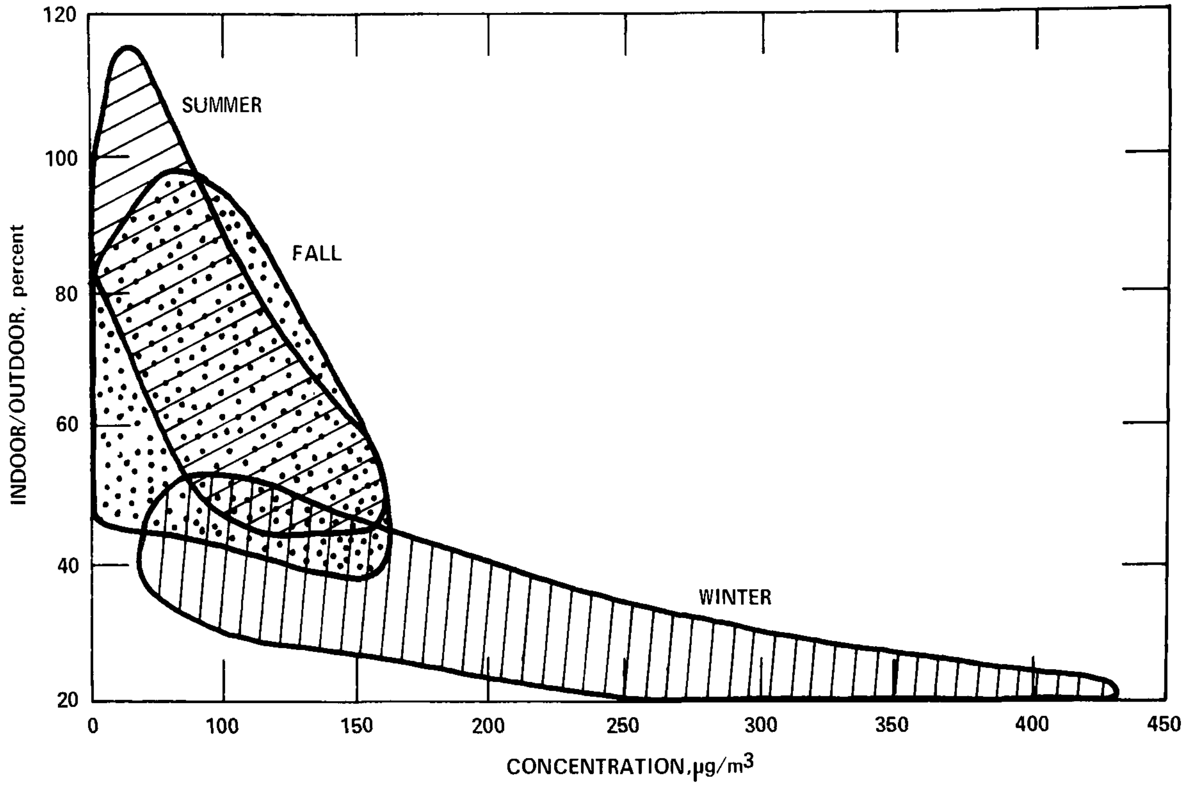

Figure 3-4. Seasonal variation of particulate concentrations and indoor/outdoor ratios in Hartford, Connecticut.[2]

occupied by the data for each season on a plot of outdoor concentration versus indoor/outdoor ratio, and which indicates a similar trend toward seasonal decrease in concentration and corresponding increase in indoor/outdoor percentage as found in the Japanese studies. Figure 3-4 also indicates that the range of outdoor concentrations is much greater during the winter, while the range of indoor/outdoor ratios is greater during the summer and fall.

Viable Particles

Spores - Indoor and outdoor spore concentrations on a monthly basis have been reported for Tucson, Arizona,[53] and Galveston, Texas.[45] For these areas, however, the data revealed no seasonal variations in either concentration or indoor/outdoor ratio except for Pullularia,[53] which was found to be more abundant from November to February.

In Copenhagen, Denmark, concentrations of many of the common spores were noted to show seasonal variations.[50] The seasons of peak concentrations were as listed on the following page.

Hormodendron - Late May to mid-October

Pullularia - Mid-September to mid-October

Alternaria - August to September

Phoma - March to October

Penicillium - None

In Lexington, Kentucky, Wallace found higher indoor and outdoor spore concentrations during the summer but higher indoor/outdoor ratios during the winter.[52]

Bacterial - In Japan, bacterial concentrations both indoors and outdoors are reported to be low from late night to early morning but high during waking hours, especially during the afternoon and evening.[14] Analysis of the data from the Japanese study on a day/night basis yields the data in Tables 3-13 and 3-14. These data indicate that outdoor bacterial concentrations are from 2 to 9 times higher during the day than during the night (Table 3-13). Indoor concentrations were also higher during the day, but not as markedly so; factors for the living room were from about 1 to 7 and those for the bedroom, excluding November, were about 1 to 1.5. In November, the concentrations in the bedroom were significantly greater at night than during the day. Indoor/outdoor percentages were generally lower during the day, and for the bedroom they were generally much lower (Table 3-14).

Table 3-13. DAY/NIGHT RATIOS OF BACTERIAL CONCENTRATIONS, TOYONAKA CITY, JAPAN[14]

Location	Day/night ratio			
	November	March	May	June
Living room	0.94	6.82	3.88	3.77
Bedroom	0.37	1.54	1.04	1.51
Outside	2.00	8.70	4.80	3.67

Table 3-14. DAY/NIGHT RATIOS OF INDOOR/OUTDOOR PERCENTAGES FOR BACTERIA, TOYONAKA CITY, JAPAN[14]

Location	Indoor/outdoor, %								Day/night ratio for indoor/outdoor %			
	November		March		May		June					
	Day	Night	Day	Night	Day	Night	Day	Night	November	March	May	June
Living room	161	344	94	119	80	99	66	64	0.47	0.79	0.81	1.03
Bedroom	228	1240	122	680	70	323	74	180	0.18	0.18	0.21	0.41

The day/night differences in indoor concentrations are thought to be the result of activities of people inside rather than of outdoor concentrations. This explains the lower day/night difference for the bedroom, which is occupied at night while the living room is not.[14]

On a seasonal basis, there is less day/night difference in concentrations but greater day/night difference in indoor/outdoor ratios in the winter than in the spring or summer. Further seasonal trends can be inferred from the data in Table 3-15. These data indicate that concentrations both indoors and outdoors generally increase from winter to summer. Summer concentrations up to 10 times winter levels have been reported.[14]

Table 3-15. BACTERIAL COUNT IN JAPAN FOR WINTER, SPRING, AND SUMMER[12,14]

Location	October-November			March			May-June		
	Indoor count	Outdoor count	Indoor/ outdoor, %	Indoor count	Outdoor count	Indoor/ outdoor, %	Indoor count	Outdoor count	Indoor/ outdoor, %
Osaka									
Apartment	27	16	169			-	28	32	87
House	71	6	1183			-	-	-	-
Toyonaka									
Living-room	8.7	5.4	161	21.1	22.6	94	35.2	45.8	77
Bedroom	12.3	5.4	228	27.6	22.6	122	32.8	45.8	72

LOCATION

Examination of the data in Tables A-1 to A-11 reveals differences in indoor pollutant concentrations and indoor/outdoor ratios on national, regional, and local levels. For instance, indoor concentrations of gaseous pollutants, specifically SO_2 and CO,[19,20,22] are exceptionally high in Russia compared with those reported in other studies, resulting perhaps from some aspect of the construction of Russian homes that makes it easier for gases to diffuse into them. The exceptionally low indoor/outdoor ratios for particulates reported in Italy and the difference in bacterial concentrations between the United States and Japan have already been mentioned. Also worthy of note are the differences in concentrations and composition of spore samples in Tables A-5 to A-9. Exceptionally high concentrations have been observed, for instance, in the coastal regions of both Spain and Texas,[45,51] with exceptionally high indoor/outdoor ratios reported for Spain. Exceptionally low concentrations characterize Arizona.

The type of area considered, that is, urban, industrial, suburban, or rural, has a great effect on the concentrations encountered, primarily because of the relative proximity of these types of areas to various sources of pollutants. As might be expected, concentrations of particulates, and probably also of gases, are higher in urban and industrial areas than in nonindustrial suburbs.[37,40] An areal study of fungus spore concentrations in Orebro, Sweden, revealed no differences in spore content, either qualitatively or quantitatively, from the city to a distance of 6 miles outside the city.[49] Fungus spore concentrations may often be higher in rural areas than in urban or suburban areas, however, because of the presence of cattle barns, storage bins, etc.[49,52]

The distance of buildings from local specific sources of pollutants plays an important role in the concentrations found inside the buildings. As expected, indoor concentrations generally become lower with increasing distance from the source.[19,22,28] In addition to such sources as industrial plants that affect a relatively large area, buildings in a much smaller area may be greatly affected by pollutants such as those generated in garages and filling stations. CO concentrations in a dwelling 18 meters from a filling station, for instance, were found to be as high as 23 ppm and to average only about 8 percent less than those near the gas pump itself.[28]

To a large extent, the effects of location discussed above pertain to outdoor as well as indoor pollution levels and could be predicted on the basis of indoor-outdoor pollution relationships such as those presented in Chapter 2 if such relationships have been established and if local outdoor concentrations are known. Consider, for instance, the data in Table 3-16 for SO_2 concentrations in the vicinity of an industrial plant.[19] In this instance, maximum concentrations outdoors decreased with distance from the plant while indoor concentrations, at this level of pollution, remained relatively constant, so that indoor concentrations as a percentage of outdoor concentrations increased. This trend is still apparent for the much lower concentrations, both indoors and outdoors, in the area beyond the influence of the plant. The patterns identified for these data and the levels of the indoor/outdoor ratios are in good agreement with the relationship delineated for SO_2 in Figure 2-1.

Table 3-16. SULFUR DIOXIDE CONCENTRATIONS IN THE VICINITY OF AN INDUSTRIAL PLANT[19]

Distance from plant, meters	Concentration, ppm		Indoor/outdoor, %
	Indoor	Outdoor	
200 to 300	0.3	1.0	30
800 to 1000	0.3	0.6	50
Beyond influence of plant	0.1	0.15	67

Even within the same building, pollution levels may not be the same in different locations. Unless they are mixed by inside activity or natural ventilation, particles and some gaseous pollutants (for example, SO_2) may be higher near the outside walls, especially at openings such as windows and doors, than in the interior of the building.[2,3] Concentrations of CO and CO_2 have been found to be higher in the upper stories of buildings.[10,29] Particulate concentrations, in contrast, may be higher in the lower stories, while oxides of nitrogen were found to be evenly distributed.[29] In some cases, internally generated pollutants, such as CO emitted from gas ranges or attached garages, can cause locally high concentrations in certain areas of a building (Figure 3-1).[3] At certain times, especially at night, dust density may vary significantly with height within the same room (Table 3-3).[14]

TYPE OF BUILDING

It seems logical to assume that indoor-outdoor pollution relationships would be different for different types of buildings,[2,69] but only a very limited amount of comparable data is available from which to evaluate the effects of building type.

Carbon Monoxide

Carbon monoxide concentrations were measured in pairs of houses, office buildings, and public buildings in Hartford.[2] As discussed in the next section, abnormally high indoor/outdoor ratios were measured at an office at 100 Constitutional Plaza (CP) because of the way in which the air conditioner was operated. Discounting these values, average indoor/outdoor ratios for the houses were about 105 percent; for the remaining office, about 95 percent; and for the public buildings, about 90 percent (Table 3-17). However, outdoor concentrations were generally lower in the vicinity of the homes than at the office and the public buildings. Thus

Table 3-17. AVERAGE CARBON MONOXIDE CONCENTRATIONS FOR SEVERAL TYPES OF BUILDINGS, HARTFORD CONNECTICUT[2]

Building	Mean concentration, ppm		Indoor/outdoor, %
	Indoor	Outdoor	
Library	3.84	4.35	88
City Hall	3.78	4.21	90
Office, 100 CP	3.21	2.69	119
Office, 250 CP	3.18	3.33	96
House, Blinn St.	2.84	2.68	106
House, Carroll Rd.	2.56	2.44	105

it is difficult to determine if the differences in indoor/outdoor ratios are related to building type or to differences in pollution levels.

Figure 3-5 is a plot of the individual CO data from the Hartford study for the range of outdoor concentrations common to all three building types. Within this range (1.5 to 3.5 ppm), data for all building types are concentrated between indoor/outdoor values of 100 and 110 percent, but values for the houses tend to be somewhat higher than those for the office and the public buildings.

Particulates

Particulate concentrations were also measured for the buildings in the Hartfort study (Table 3-18). Average indoor/outdoor ratios for the houses were around 65 percent; for the office, around 45 percent; and for the public buildings, around 35 percent. Again, however, outdoor pollution levels were lower in the vicinity of the houses.

Figure 3-6 is a plot of the data for the range of common outdoor concentrations. A limited amount of data from Whitby et al.[38] which can be plotted in the same form is included for comparison. Outdoor concentrations for the homes fall between about 50 and 125 $\mu g/m^3$. Data for the offices and public buildings for this level of pollution generally fall within the data scatter band for the houses, but are concentrated in the lower portion of the band.

Presuming the outdoor concentrations to be similar, additional comparisons of this type can be made from the data reported in References 30, 32, and 33.

Other Factors Affecting Indoor Concentrations

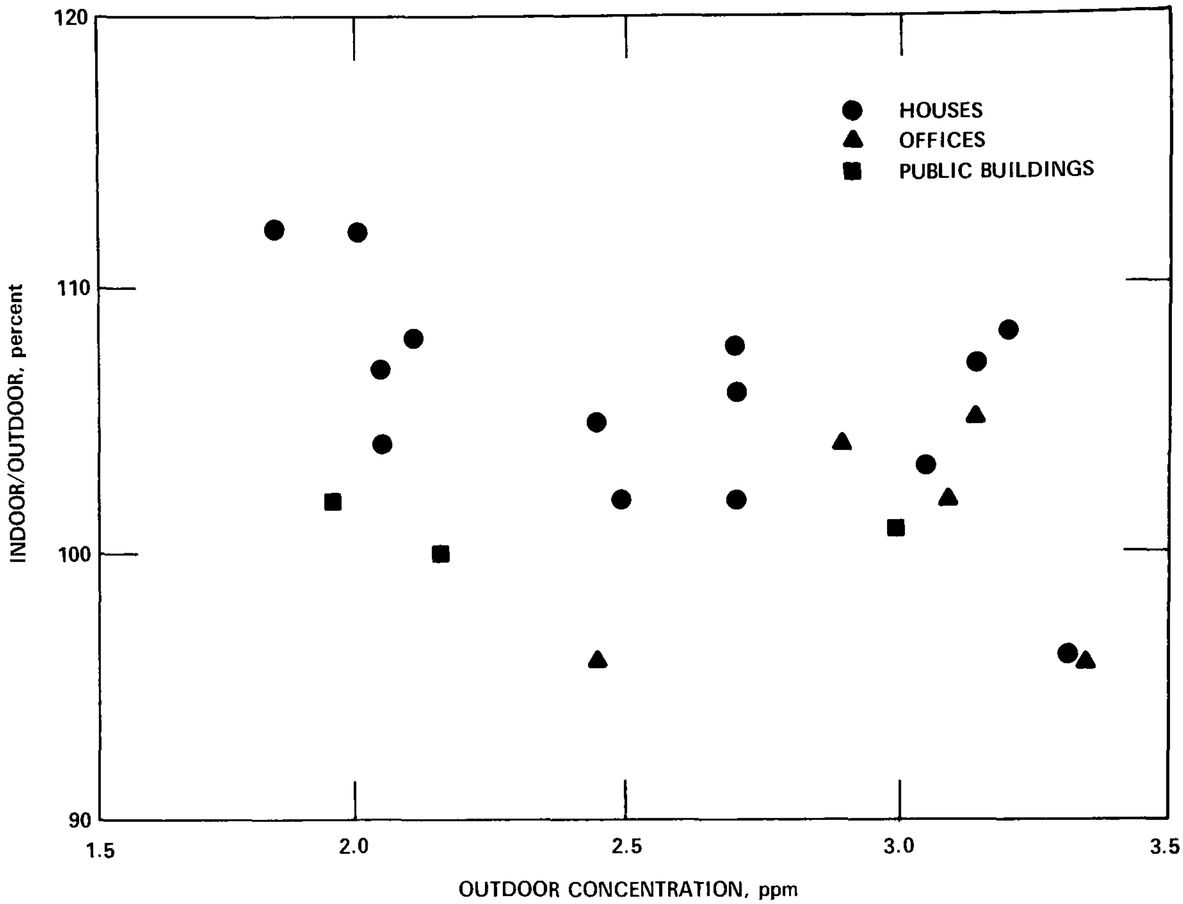

Figure 3-5. Effect of type of building on indoor/outdoor carbon monoxide concentrations.[2]

Table 3-18. AVERAGE PARTICULATE CONCENTRATIONS FOR SEVERAL TYPES OF BUILDINGS, HARTFORD CONNECTICUT[2]

Building	Mean concentration, $\mu g/m^3$		Indoor/outdoor, %
	Indoor	Outdoor	
Library	45	189	26
City Hall	66	159	42
Office, 100 CP	39	81	48
Office, 250 CP	45	104	43
House, Blinn St.	52	86	60
House, Carroll Rd.	54	75	72

Reference 30 reports indoor ranges of 60 to 539 $\mu g/m^3$ for houses and 95 to 232 $\mu g/m^3$ for offices and public buildings. These data support the trend noted for Figure 3-6. References 32 and 33 report ranges of 50 to 1230 particles/cm^3 for

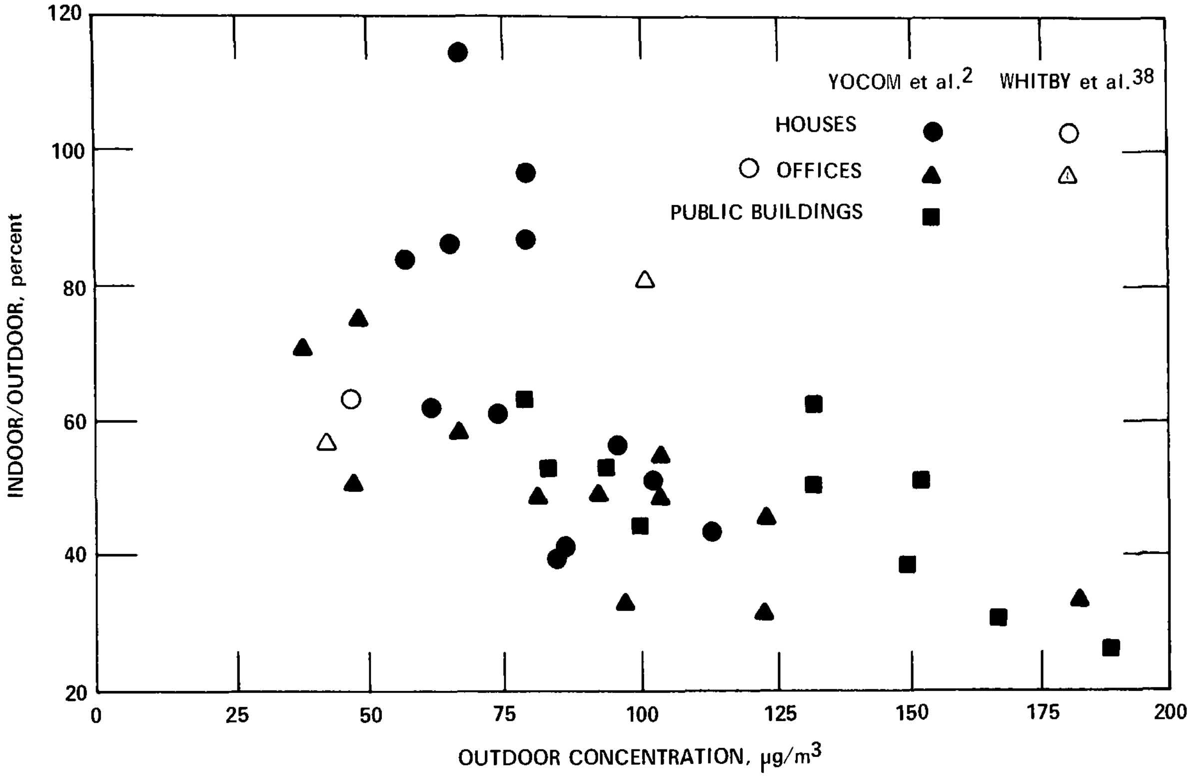

Figure 3-6. Effect of type of building on indoor/outdoor particulate concentrations.

houses and 141 to 1880 particles/cm^3 for offices and public buildings. In this instance, lower concentrations are reported for houses, but the ranges are still similar.

Summary

Based on the limited CO and particulate data available (primarily from Yocum et al. 1971),[2] it appears that indoor-outdoor pollution relationships are not greatly different for the pollutants, building types, and ranges of outdoor concentrations for which comparable data are available. These data are limited, however, to CO concentrations between 1.5 and 3.5 ppm and, primarily, to particulate concentrations between 50 and 125 µg/m^3. For these pollutants at these concentrations, pollution levels inside houses appear to be slightly higher than those inside offices and public buildings when similar outdoor concentrations prevail.

AIR CONDITIONING AND FILTRATION

Air-conditioning engineers are confident that air-conditioning systems can be designed, built, and operated to remove air pollutants so that indoor air in buildings and vehicles will be continuously comfortable and free from the stress effects of air pollution.[70] It has been alleged, however, that "in contrast to what most people comfortably assume, much of the pollution of the outdoor air enters our buildings directly through the air conditioning equipment as supplied and installed today," and the data with which to refute this charge have yet to be gathered.[7] It has been noted instead that the current employment of air conditioning is largely dictated by the economics of heating and cooling with little regard for changes in indoor air quality and how it is affected by outside pollutant levels, by air-conditioning system parameters, and by internal pollutant generation.[1] The data available in the current literature, reviewed in the following sections, may shed some light on these conflicting allegations.

Gases

A recent study in Boston, Massachusetts, indicated that SO_2 concentrations were reduced to 60 percent of outside levels simply by bringing the air inside and that further reductions were not effected by air-conditioning systems unless the systems included water sprays on the cooling coils. This study also revealed that ozone concentrations indoors were not generally affected by air conditioning. Air-conditioning systems with electrostatic precipitators actually caused a slight increase in ozone concentrations, but never enough to be of concern.[7]

Carbon monoxide, being unreactive, is not effectively removed by air-conditioning.[5,70] Substantiation for this statement can be seen in Figure 3-5 and Table 3-17. The two office buildings in the Hartford study were air conditioned, but indoor/outdoor ratios were consistently near 100 percent for the office at 250 CP, and Figure 3-4 shows that there was little difference between that office and the non-air-conditioned houses and public buildings investigated for the range of common outdoor levels. Indoor/outdoor percentages for the office at 100 CP were consistently higher than for either the other office or the non-air-conditioned buildings.

The higher indoor/outdoor ratios for the office at 100 CP are thought to be directly related to the air-conditioning system and its method of operation. "Stale" air trapped in the building during the overnight shutdown was purged each morning with "fresh" air drawn from the outside. This "fresh" air, however, was drawn from near street level during the time of the morning peak traffic period. The dilution of this initial "charge" of CO provided by the 10 percent make-up air used during the remainder of the day was apparently not sufficient to reduce the indoor concentrations to the vicinity of the outdoor levels.[1]

Particulates

The available literature indicates that air-conditioning systems can significantly reduce indoor particulate concentrations when efficient filters are employed. An air-conditioning system that maintained a positive interior pressure was found to reduce indoor concentrations to 24 percent of outdoor levels.[42] This system employed two filters with high dust-removal efficiency. Electrical dust collectors have also been noted to be highly effective in eliminating indoor suspended particulate matter.[9] In the Boston study, significant reductions were noted for a building with a central air-conditioning system having, in succession, an electrostatic precipitator, a roll screen backing filter, water spray, and cooling coils.[7]

Yocom et al. (1971)[2] concluded that the roughing filters normally used in air-conditioning systems are also at least moderately effective in removing particulates. This conclusion is based on the fact that indoor/outdoor percentages for the two air-conditioned offices sampled in the Hartford study averaged less than 50 percent. However, when the data are examined for the range of common outdoor concentrations as in Figure 3-6, indoor/outdoor ratios are not found to be reduced when compared with the non-air-conditioned public buildings nor even consistently reduced when compared with the houses. Thus, it is not clear whether the apparent reduction at the offices was a result of the air-conditioning system or was, in fact, a result of higher outdoor pollution levels. Significant reductions in indoor particulate levels for the Boston study were found only for the air-conditioning system described above. In five other air-conditioned buildings, indoor-outdoor relationships were about what one would expect for non-air-conditioned buildings.[7,8]

Viable Particles

Pollen appears to be the only pollutant which is unequivocally reported to be reduced by air conditioning. Comparative concentrations for air-conditioned and non-air-conditioned buildings are presented in Table 3-19. These data indicate that air conditioning significantly improves indoor pollen concentrations. Indoor/outdoor ratios for air-conditioned rooms or buildings range from 0.2 to 2 percent, whereas those for non-air-conditioned rooms or buildings in companion tests range from 6 to 68 percent. Some types of air filtration and purification devices were found to be effective in reducing pollen,[61,63,65] but the device evaluated by Spiegelman et al.[60] actually appeared to increase indoor pollen concentrations. In conjunction with an air conditioner, neither the standard air-conditioner filter[60] nor the special filter evaluated by Speigelman and Friedman[59] was found to improve indoor pollen concentrations more than the air conditioner alone.

Concentrations of bacteria and spores may also be lower in air-conditioned buildings, but the data are highly limited and inconclusive. In one study, mold and bacteria in an air-conditioned room were found to be only 9 percent of those in a non-air-conditioned room with windows open.[60] But in another study by the same authors, mold counts ranged from 0 to 20 colonies/dish in a non-air-conditioned house and from 0 to 25 colonies per dish in an air-conditioned house, while bacteria counts in both houses ranged from 0 to 45 colonies/dish.[43]

Summary

The data available in the literature appear to support the conclusion drawn from the Boston study: i.e., the improvement in air quality obtained with air conditioning is dependent on the type of air cleaning equipment incorporated in the system; the more sophisticated (and expensive) the equipment, the better the job.[7] Carbon monoxide, nitric oxide, and light hydrocarbons are difficult to remove without extensive pretreatment of the intake air.[70] Sulfur dioxide is not removed by standard air-conditioner components unless they include water sprays. Particulate concentrations may be reduced slightly by the roughing filters commonly used in air conditioners, but more efficient filters must be used to obtain significant reductions. Pollen, in contrast to other pollutants, is practically eliminated by air conditioning, even without the standard roughing filters normally employed.

Although they are not generally employed in the air-conditioning systems currently in use, air filtration and purification devices that could significantly reduce the indoor concentrations of most pollutants are available. Evaluations of the efficiency, application, and cost of those components are properly the subject of a separate report and are not covered here. Holcombe and Kalika[6] and Parnell[71] present such evaluations. In addition, Kalika et al.[1] include suggestions concerning the design and operation of air-conditioning systems to reduce indoor pollution.

Table 3-19. EFFECT OF AIR CONDITIONERS, FILTERS, AND PURIFIERS ON INDOOR POLLEN CONCENTRATIONS AND ON INDOOR/OUTDOOR RATIOS

Reference	Location	Building type	Measurement	Concentration				Indoor/ Outdoor, %	Remarks	
				Range		Mean				
				Indoor	Outdoor	Indoor	Outdoor			
63	Pittsburgh, Pennsylvania	Hospital	Pollen count	-	-	144	1,539	9.4	Without air filter	
				-	-	0	1,539	0	With air filter	
64	Richmond, Virginia	Hospital	Grains/day	7 to 407	71 to 1,188	-	-	23	Non-air-conditioned room	
				0 to 2	71 to 1,188	-	-	0.2	Air-conditioned room	
65	Chicago, Illinois	Hospital	Grains/cm^2	0 to 23	10 to 350	6	133	4.5	With air filter	
43	Philadelphia, Pennsylvania	Houses	Grains/m^3	0 to 74	0 to 1,100	-	-	6	Without air conditioner	
				0 to 28	0 to 1,100	-	-	2	With air conditioner	
59	Philadelphia, Pennsylvania	Houses		--	2 to 1,100	11	205	5	Non-air-conditioned house	
				-	2 to 1,100	11	205	5	Air conditioner and air filter off	Test house
				-	2 to 1,100	2	205	1	Air filter off	
				-	2 to 1,100	2	205	1	Air conditioner and air filter on	
60	Philadelphia, Pennsylvania	Hospital		12.7 to 98.2	31.9 to 110	42.2	61.8	68	Windows open	No filter in air conditioner
				12.4 to 141	31.9 to 110	53.5	61.8	86	Windows open with air purifier	
				0.4 to 2.8	31.9 to 110	1.6	61.8	2	Air conditioned	
				0.4 to 2.8	31.9 to 110	1.0	61.8	2	Air conditioned with air purifier	
				11.9 to 68.3	60.0 to 272	33.8	119	28	Windows open	Standard filter in air conditioner
				26.8 to 82.0	60.0 to 272	57.9	119	49	Windows open with air purifier	
				0.7 to 2.6	60.0 to 272	1.6	119	1	Air conditioned	
				0.7 to 6.6	60.0 to 272	2.6	119	2	Air conditioned with air purifier	
61	Chicago, Illinois	Hospital		6.6 to 392	14.4 to 914	92.8	262	36	Without air filter	
				1.3 to 23.6	14.4 to 919	7.9	262	3	With air filter	

CHAPTER 4.
INSTRUMENTATION AND PROCEDURES

A general discussion of air pollution measurement techniques is not within the scope of this report. Discussions of techniques and methods are presented, however, in References 71 through 74.

Measurement of pollution indoors presents problems that are not encountered in outdoor measurements. For instance, noisy air samplers, such as the standard high volume sampler, are not acceptable inside buildings or near residences.[2] In addition, the high flow rate of such instruments can affect the results obtained by modifying the ventilation rate of the room being sampled.[2,30]

Particle size distributions are especially important for indoor-outdoor measurements. As with outdoor pollution, particle size is important because it is related to sedimentation, soiling, and health effects.[2,71] In addition, as discussed in Chapter 2, it appears that particles of different sizes may penetrate buildings at different rates.

Yocum et al. (1971)[2] have described a portable, self-contained instrument package developed especially for indoor/outdoor sampling for particulates and gases. Some modifications have been made to their system in order to overcome operational difficulties experienced in early testing and to make possible the determination of particle size distribution.[5] Reference 75 describes the gas analysis equipment used on submarines. This equipment should be effective and compact and could possibly be employed in indoor pollution measurements. Reference 16 describes a small sequence sampler for determining indoor sulfur dioxide concentrations. A tape sampler for determining particulate concentrations is described in Reference 41, and Reference 76 describes methods for determining size distributions as well as concentrations with this type of sampler. Reference 48 includes a discussion of the comparative limitation of sedimentation and the advantages of impaction for obtaining samples of airborne viable particles.

The review of literature revealed many shortcomings in the methods that have been used for obtaining, analyzing, and presenting indoor-outdoor pollution data. These shortcomings resulted in part from a lack of suitable instrumentation at the time some of the studies were conducted, but to a larger extent they resulted from a lack of basic knowledge of indoor-outdoor pollution relationships and the factors that affect these relationships. The data obtained were sufficient, however, to define possible trends and identify the factors that probably affect the relationships. Based on the information gathered in this review, recommendations concerning the techniques to be employed in future studies are offered in Chapter 5.

CHAPTER 5.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Although indoor-outdoor pollution measurements have been presented in a large number of references, examination of Tables A-1 to A-9 reveals that the amount of reliable and readily comparable data must still be considered highly limited. Thus, the conclusions resulting from this review must be regarded as merely tentative.

Indoor-Outdoor Concentrations

Except for bacteria and, perhaps, for fungus spores, indoor pollution levels appear to be controlled primarily by outdoor concentrations.

Under normal circumstances, the best available estimate for indoor concentrations of particulates and CO (and probably other nonreactive gases as well) can be obtained by presuming them equal to outdoor concentrations. It is possible that indoor concentrations of these pollutants are lower than outdoor levels when outdoor concentrations are high, but the available data do not definitely establish this relationship.

A fairly well established relationship of decreasing indoor/outdoor concentration ratios with increasing outdoor concentrations of SO_2 has been identified as shown in Figure 2-1. This relationship may also be generally applicable for other reactive gases, but no data are available with which to support this supposition or with which to evaluate the amount of decrease in relation to the degree of reactivity.

Indoor pollen counts, as a percentage of outdoor counts, also appear to become lower with increasing outdoor concentrations (Figure 2-3) but this relationship is not as well substantiated as that for SO_2.

Indoor bacterial concentrations have been found to be more closely related to the presence and activities of people inside than to outdoor concentrations.

Some investigators have concluded that the major source of airborne spores in normal dry, clean houses is the outdoor air. Differences in the composition of indoor and outdoor spore populations reported in a number of the publications reviewed do not appear to support this contention, however.

Other Factors Affecting Indoor Concentrations

Although outdoor concentrations exert a controlling influence on indoor concentrations in most situations, a number of other factors have been identified as affecting, or have been hypothesized to affect, the indoor-outdoor relationship. These factors include internal activities and pollutant generation, atmospheric conditions and natural ventilation, time, location, air conditioning and filtration, and type of building. The effects of these factors must be considered if accurate estimates and meaningful measurements of indoor concentrations are to be made.

Internal Activities and Pollutant Generation - Pollutants, including CO, SO_2, and particulates, can be generated by interior activities that involve combustion; e.g. smoking, cooking, heating. In addition, activities of people inside play a large part in the entrainment and distribution of pollutants. Internal generation is suspected to be responsible for a great deal of the scatter in reported results and for some measured indoor concentrations that were higher than outdoor concentrations. No quantitative measurements of internal generation have been presented however.

Atmospheric Conditions and Natural Ventilation - Although such factors as temperature, humidity, and precipitation might be presumed to influence indoor-outdoor pollution relationships, no correlations could be established in the few studies in which these conditions were reported. Wind speed and direction have been found to affect the relationship in a number of instances, however. Closely associated with these factors is the amount of natural ventilation of the building; i.e., its tightness and window and door openings. Very few data are available from which to evaluate the effects of natural ventilation, but, in general, increased natural ventilation appears to facilitate the penetration of pollutants into buildings.

Time - Indoor concentrations, outdoor concentrations, and indoor/outdoor ratios have been found to vary on daily and seasonal bases. Much of the variation in indoor/outdoor ratio can probably be explained by changes in outdoor concentrations or in other factors discussed in this section. For instance, indoor/outdoor ratios for particulate concentrations have been found to be lower in winter than in summer, possibly because outdoor concentrations are higher during the winter or because natural ventilation decreases when buildings are shut up for the winter.

One time-dependent factor, the so-called "lag time," affects indoor-outdoor relationships independently, although lag time itself is affected by such factors as natural ventilation. For many pollutants, indoor concentrations react more slowly to changes in overall ambient air pollution than do outdoor concentrations. This difference in reaction time can result in lower inside concentrations since sharp outdoor peaks may be smoothed by the lag-time effect. It can also result in indoor concentrations higher than outdoor concentrations when outdoor concentrations are falling. This effect is suspected as the cause in many of the instances when indoor/outdoor percentages greater than 100 percent were reported. Lag times have been identified for CO, SO_2, and particulates, but no method is available for predicting their occurrence or effect.

Location - Indoor concentrations and indoor/outdoor ratios have been found to vary nationally, regionally, and locally. For the most part, however, these variations are related to variations in outdoor concentration and can be predicted if local outdoor concentrations are known. It should be kept in mind, however, that outdoor concentrations and the resulting indoor concentrations can vary widely within a small area depending on such factors as wind direction relative to major pollution sources and the presence of locally significant sources such as garages and filling stations.

Even within the same building, pollution levels may not be the same in different locations. Variations have been identified from room to room, from story to story, and even from floor to ceiling and from exterior to interior walls within the same room.

Type of Building - It seems logical to assume that indoor-outdoor pollution relationships would be different for different types of buildings. Examination of the limited amount of comparable data for the range of common outdoor concentrations does not reveal a great deal of difference, however.

Air Conditioning and Filtration - Air-conditioning engineers are confident that air-conditioning systems can be designed, built, and operated to remove air pollutants. The degree of improvement in air quality obtained with air conditioning is dependent, however, on the type of air-cleaning equipment incorporated in the system. Given the types of air-conditioning systems normally supplied up until around 1970, air conditioning has very little effect on interior air quality.

Pollen is indeed practically eliminated by air conditioning, even without the standard roughing filters normally employed, and coarser particles may be reduced by the standard filters; but other pollutants and smaller sized particles are generally unaffected. Components are available that can reduce certain types of pollution, and their use has received more attention in recent years.

Summary

Indoor air pollution is controlled primarily by outdoor pollution. The relationship is far from simple, however. It is affected by a large number of factors, all of which must be considered if accurate estimates and meaningful measurements of indoor concentrations are to be made. The data currently available are sufficient only to suggest general patterns in the relationship between indoor and outdoor pollution, and the effects of factors other than outdoor concentration are even less well defined.

RECOMMENDATIONS

The conclusions presented above are admittedly tentative. They are thought, however, to constitute the best basis currently available for estimating indoor pollution, and they are recommended for this purpose until better information is available.

Additional experimental work is badly needed to test the validity of these conclusions, and it is suggested that the conclusions be considered in planning and evaluating future studies. Some of the needed data are already being obtained or analyzed. The Research Corporation of New England (formerly The Travelers Research Corporation) and Arthur D. Little, Inc., are conducting research in continuation of the studies reported in References 1 to 6 and in References 7 and 8, respectively. The General Electric Company[77] has also conducted research that should help to better define indoor-outdoor pollution relationships, and the result of these studies should also be considered in planning future studies if they are available.

Review of the various studies and of the publications in which they are described has lead to some suggestions which may be of value in planning, conducting, and reporting future indoor-outdoor air pollution studies. First, because of the strong dependence of indoor concentrations on outdoor concentrations, outdoor concentrations should be measured in any study in which indoor pollution is to be evaluated. If possible, both indoor and outdoor sampling should be conducted over a period of at least several hours and the samples should be taken as simultaneously as possible because of lag-time effects.

In planning future studies, pollution sources both indoors and outdoors should be considered. Several sampling points may be necessary inside and out to determine the actual outdoor concentrations to which indoor levels are responding, the influence of interior pollution sources, and the degree and rate of pollutant penetration. Activities inside the building being sampled should be controlled, limited, or at least recorded and considered in evaluating the results.

For particulate measurements, particle size distributions both indoors and out should be determined, if possible, since particles of different sizes have different effects and may penetrate buildings at different rates. When bacteria and fungi are measured, the types should be identified, if possible, and spore sizes should be considered in analyzing the results to determine if differences in composition between indoor and outdoor population are the result of interior generation or of selective penetration. Some method of normalizing results of fungus and bacteria sampling is badly needed to facilitate comparison of results.

Since indoor-outdoor pollution relationships are highly complex and all of the factors affecting the relationship may not yet be identified, it is very important that test conditions and procedures be described in detail. At least those factors discussed earlier in this chapter under "Other Factors Affecting Indoor Concentrations," as well as sampling locations, procedures, and instrumentation, should be described. Emphasis on test conditions and procedures should not be such, however, that presentation and analysis of the results becomes secondary.

Analysis of results should begin with consideration of indoor-outdoor relationships since outdoor concentrations have been identified as exerting a controlling influence. Any other relationships developed in further analysis of the results should also be examined for possible contributing factors such as those discussed earlier.

Many of the publications reviewed in this survey were journal articles. Since journal articles are necessarily general and limited in scope, some method needs to be found to make the detailed data on which such articles are based readily available so that they can be considered for applications beyond the scope of the published article. As an example, the American Institute of Chemical Engineers places such data on file with the American Documentation Institute.

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APPENDIX A.

COMPILATION OF INDOOR-OUTDOOR AIR POLLUTION DATA

Table A-1. INDOOR AND OUTDOOR CONCENTRATIONS OF SULFUR DIOXIDE

Location	Building type	Concentration, pphm		Indoor/ outdoor, %	Remarks
		Indoor	Outdoor		
Hartford, Conn.[3]	House (Blinn St.)	1.4	0.4	350	Day
		0.3	0.1	300	Night
		0.8	0.2	400	Average
	House (Carroll Rd.)	3.7	0.0	∞	Day
		2.8	0.3	935	Night
		3.2	0.2	1600	Average
Hartfort, Conn.[a,4]	Houses	78	10	780	Old coal-heated house[b]
		5	14	36	New coal-heated house
Cincinnati, Ohio[16]	Hospital	6	8	75	
		10	16	62	
		12	24	50	
		14	32	44	
		16	40	40	
		18	48	37	
Moscow, U.S.S.R.[19]	Houses	30	100	30	200 to 300 meters from industrial plant
		30	60	50	800 to 1000 meters from industrial plant
		40	70	57	Area away from industrial plant
		10	15	67	Botanical garden (control area)
U.S.S.R.[20]	Houses	38	42	90	Near viscose plant
Rotterdam[21]	House	1.52	7.47	20	

[a]Maximum concentrations are listed. Concentrations for other studies are mean values.

[b]High inside concentrations are presumed to be caused by a faulty heating system. Excluded from Figure 2-1.

Table A-2. INDOOR AND OUTDOOR CONCENTRATIONS OF CARBON MONOXIDE

Location	Building type	Season	Time	Distance from source, m	Concentration, ppm		Indoor outdoor, %
					Indoor	Outdoor	
Hartford, Conn.[2]	Library	Summer	Day		3.24	3.73	87
			Night		2.17	2.17	100
		Fall	Day		4.76	6.14	78
			Night		4.52	4.72	96
		Winter	Day		5.28	6.32	84
			Night		3.06	3.02	101
		Average			3.84	4.35	88
	City Hall	Summer	Day		3.04	3.40	89
			Night		2.00	1.97	102
		Fall	Day		4.35	4.90	89
			Night		3.83	3.78	101
		Winter	Day		6.02	7.50	80
			Night		3.45	3.71	93
		Average			3.78	4.21	90
	Office (100 CP)	Summer	Day		3.34	2.55	131
			Night		2.81	2.80	100
		Fall	Day		3.58	2.72	132
			Night		2.48	1.99	125
		Winter	Day		3.82	3.39	113
			Night		3.25	2.69	121
		Average			3.21	2.69	119
	Office (250 CP)	Summer	Day		3.42	3.26	105
			Night		3.18	3.11	102
		Fall	Day		3.83	4.01	96
			Night		3.05	2.92	104
		Winter	Day		3.23	4.26	76
			Night		2.34	2.43	96
		Average			3.18	3.33	96
	House (Blinn St.)	Summer	Day		2.57	2.52	102
			Night		3.36	3.14	107
		Fall	Day		3.17	3.06	103
			Night		3.48	3.21	108
		Winter	Day		2.21	2.05	107
			Night		2.27	2.09	108
		Average			2.84	2.68	106
	House (Carroll Rd.)	Summer	Day		2.15	2.06	104
			Night		2.75	2.70	102
		Fall	Day		3.20	2.33	96
			Night		2.94	2.70	108
		Winter	Day		2.07	1.84	112
			Night		2.23	1.99	112
		Average			2.56	2.44	105
Moscow, U.S.S.R.[22]	Houses			50[a]	11.6	17.8	65
				100[a,b]	16.3	16.5	99
				250[a]	9.0	14.9	60
				500[a]	7.6	12.8	59
				300[c]	39.9	48.8	82
				800 to 1000[c]	22.4	34.1	66

[a]Source was plant with open hearth furnace.

[b]Natural-gas equipped. Other homes in Russian study were not. Excluded from Figure 2-1.

[c]Source was plant with blast furnace.

Table A-3. INDOOR AND OUTDOOR CONCENTRATIONS OF GASEOUS POLLUTANTS OTHER THAN SO_2 AND CO

Gas	Location	Building type	Concentration, pphm[a]				Indoor outdoor, %	Remarks
			Range		Mean			
			Indoor	Outdoor	Indoor	Outdoor		
Carbon dioxide[a]	Osaka, Japan[10]	Offices	0.06 to 0.32	-	-	-	-	Office building
			0.08 to 0.28	-	-	-	-	Old office building, winter
			0.04 to 0.09	-	-	-	-	Old office building, summer
			0.06 to 0.23	-	-	-	-	New air-conditioned building, winter
			0.04 to 0.13	-	-	-	-	New air-conditioned building, summer
			0.03 to 0.14	0.03 to 0.04	-	-	-	Newer air-conditioned building
Nitrogen dioxide	Los Angeles, California[23]	House	0 to 9.5	1 to 12.5	3.1	-	-	Room with activated carbon filter
			1 to 11.5	1 to 12.5	3.1	-	-	Room with no filter
				1 to 12.5	5.5	-	-	Room with particulate filter
				1 to 12.5	6.3	-	-	Room with no filter
Carbon bisulfide	U.S.S.R.[20]	Houses	-	-	4	5	80	Near viscose plant
Hydrogen sulfide	U.S.S.R.[20]	Houses	-	-	6	9	67	Near viscose plant
Total gaseous acid	Cincinnati, Ohio[17]	Old peoples' home	3.3 to 13	1.8 to 14	7.7	5.9	131	Windows open
			0 to 3.5	1.8 to 14	2.0	5.9	34	Windows closed
	Cincinnati, Ohio[18]	Houses	-	-	2.4	4.7	51	

[a]Carbon dioxide concentration in percent.

Table A-4. INDOOR AND OUTDOOR CONCENTRATIONS OF PARTICULATES

Location	Building type	Season or month	Time	Measurement	Concentration: Range, Indoor	Concentration: Range, Outdoor	Concentration: Mean, Indoor	Concentration: Mean, Outdoor	Indoor/outdoor, %
Hartford, Conn.[2]	Library	Summer	Day	Weight, $\mu g/m^3$			66	132	50
			Night				43	82	52
		Fall	Day				57	150	38
			Night				44	100	44
		Winter	Day				67	425	16
			Night				45	189	26
		Average					54	180	30
	City Hall	Summer	Day				78	153	51
			Night				49	78	63
		Fall	Day				82	133	62
			Night				50	94	53
		Winter	Day				87	327	27
			Night				51	168	30
		Average					66	159	42
	Office (100 CP)	Summer	Day				50	104	48
			Night				46	93	49
		Fall	Day				36	48	75
			Night				27	38	71
		Winter	Day				38	124	31
			Night				39	81	48
		Average					39	81	48
	Office (250 CP)	Summer	Day				56	124	45
			Night				60	109	55
		Fall	Day				38	66	58
			Night				23	46	50
		Winter	Day				60	183	33
			Night				32	97	33
		Average					45	104	43
	House (Blinn St)	Summer	Day				70	79	87
			Night				56	65	86
		Fall	Day				54	96	56
			Night				45	74	61
		Winter	Day				49	114	43
			Night				35	86	41
		Average					52	86	60
	House (Carroll Rd)	Summer	Day				76	66	115
			Night				47	56	84
		Fall	Day				76	78	97
			Night				38	61	62
		Winter	Day				53	103	51
			Night				33	85	39
		Average					54	75	72
New York, N. Y.[30]	Offices				95 to 211				
	Laboratories				157 to 232				
	Living rooms				60 to 539				
	Bedrooms				61 to 250				
	Overall				60 to 539	41 to 938	158	212	75
West Queens, N.Y.[31]	Houses				90 to 462	101 to 480	239	226	106
Dushambee, U.S.S.R.[29]	Houses[a]								
	First story						1270	960	132
	Second story						660	960	60
Rotterdam, Netherlands[21]	Houses						153	184	83
London, England[25,26]	Laboratory				77 to 625	75 to 800	195	205	95
New York, N.Y.[32,33,b]	Offices			Particle count, particles/cm^3	141 to 1880				
	Laboratories				152 to 740				
	Living rooms				50 to 860				
	Bedrooms				148 to 1230				
	Overall				50 to 1880	74 to 1800	378	512	74
Cincinnati, Ohio[34]	Laboratory						460	120	380
Osaka, Japan[12,13]	Apartment	November			570 to 4200	509 to 5009	-	1897	
		March			294 to 3714	372 to 4028	1287	1528	84
		May			230 to 2886	245 to 2874	978	1047	91
		June			278 to 1494	295 to 1303	738	752	98

Table A-4 (continued). INDOOR AND OUTDOOR CONCENTRATIONS OF PARTICULATES

Location	Building type	Season or month	Time	Measurement	Concentration: Range, Indoor	Concentration: Range, Outdoor	Concentration: Mean, Indoor	Concentration: Mean, Outdoor	Indoor/ outdoor, %
Osaka, Japan[11]	Apartment			Particle count, Particles/cm3	4 4 to 1747	296 to 2058	706	619	114
	Residential store				83 to 2144	117 to 1790	662	678	98
	Hospital				421 to 4195	410 to 4166	1611	1595	101
	School				513 to 7439	627 to 7592	2382	2346	102
Toyonaka, Japan[14]	Apartment Bedroom	November	Day				1654	2133	78
			Night				1839	1839	100
		March	Day				1497	1801	83
			Night				1115	1319	85
		May	Day				1091	1129	97
			Night				1001	1060	95
		June	Day				726	703	103
			Night				807	786	103
		Average					1216	1346	90
	Living room	November	Day				1839	2133	86
			Night				1899	1839	103
		March	Day				1602	1801	89
			Night				1081	1319	82
		May	Day				931	1129	82
			Night				1020	1060	96
		June	Day				670	703	95
			Night				732	786	93
		Average					1222	1346	91
Novara, Italy[37]	Schools Urban						368	662	56
	Suburban-residential						258	280	92
	Suburban-industrial						340	752	45
	Rural						444	690	64
Hartford, Conn.[2]	Library	Summer	Day	Soiling index, Cohs/1000 linear ft			0.34	0.42	81
			Night				0.25	0.31	81
		Fall	Day				0.33	0.36	92
			Night				0.32	0.34	94
		Winter	Day				0.29	0.58	50
			Night				0.24	0.49	49
		Average					0.30	0.42	72
	City Hall	Summer	Day				0.40	0.41	98
			Night				0.30	0.30	100
		Fall	Day				0.38	0.33	115
			Night				0.33	0.29	114
		Winter	Day				0.49	0.52	94
			Night				0.41	0.44	93
		Average					0.38	0.38	100
	Office (100 CP)	Summer	Day				0.26	0.30	87
			Night				0.30	0.36	83
		Fall	Day				0.19	0.27	69
			Night				0.19	0.24	79
		Winter	Day				0.35	0.41	85
			Night				0.34	0.38	89
		Average					0.27	0.33	82
	Office (250 CP)	Summer	Day				0.26	0.46	57
			Night				0.32	0.52	62
		Fall	Day				0.22	0.28	79
			Night				0.21	0.25	84
		Winter	Day				0.42	0.72	58
			Night				0.35	0.64	55
		Average					0.30	0.48	63
	House (Blinn St)	Summer	Day				0.39	0.44	89
			Night				0.45	0.53	85
		Fall	Day				0.30	0.33	88
			Night				0.31	0.35	89
		Winter	Day				0.33	0.40	82
			Night				0.37	0.50	74
		Average					0.36	0.42	86
	House (Carroll Rd)	Summer	Day				0.38	0.32	119
			Night				0.42	0.38	110
		Fall	Day				0.26	0.34	80
			Night				0.24	0.36	67
		Winter	Day				0.27	0.29	93
			Night				0.30	0.36	83
		Average					0.31	0.34	91
Cincinnati, Ohio[18]	Houses						2.1	3.8	55

[a]Near main traffic.

[b]Concentrations reported in particles per cubic foot; conversion accurate to three significant digits.

Table A-5. INDOOR AND OUTDOOR CONCENTRATIONS OF FUNGUS SPORES

Location	Building type	Duration of exposure, minutes	Measurement	Concentration: Range, Indoor	Concentration: Range, Outdoor	Concentration: Mean, Indoor	Concentration: Mean, Outdoor	Indoor/outdoor, %	Remarks
Philadelphia, Pennsylvania[43]	Houses	15	Colonies/sample	0 to 25	0 to 35			72[a]	Room with air conditioner
				0 to 20	0 to 35			52[a]	Room without air conditioner
St. Paul, Minnesota[44]	Houses	12		0 to 23		8			Early morning
				0 to 28		11			Before sweeping
				4 to 46		22			After sweeping
				0 to 13		5			Late evening
					13 to 80	12	38	32	Overall
Galveston, Texas[45]	Office	2		5 to 34	7 to 32	16.3	12.9	126	Colonies/sample-day
London, England[45]	Houses	-		33 to 115	38 to 125	60	76	79	
Oereboro, Sweden[49]	Houses	30				5	13	38	Dry, clean conditions
						55	13	423	Poor hygenic conditions
Copenhagen, Denmark[50]	Houses	15				30.4	35.3	86	
Madrid, Spain[51]	-	-	Colonies/m^3			1,808	478	378	
Spanish coast[51]	-					1,187	515	230	
Lexington, Kentucky[52]	Theater and two houses	15	Total colonies			1,199	3,978	30	Summer
						224	306	73	Winter
Tucson, Arizona[53]	Houses	15				203	1,209	17	Air conditioned
						208	1,209	18	Air conditioned with filter
						422	1,209	35	Evaporative cooler
Cardiff, Wales[54]	House	10				1,289	6,859	19	
Stockholm, Sweden[55]	House and office	-				6,135	12,712	48	
Copenhagen, Denmark[56]	Apartment	15				5.7	10.0	57	
Cardiff, Wales[57]	Hospital	-	Grains/m^3			205	2,609	7.9	
	Hospital	-				506.	6,520	7.8	
	Public building	-				89.7	6,896	1.3	
Stockholm, Sweden[58]	Public building	-	Total colonies			540	1,572	34	

[a]Based on maximum concentrations.

Table A-6. INDOOR AND OUTDOOR CONCENTRATIONS OF SPECIFIC FUNGUS SPORES

Fungus	Reference	Mean concentration[a]		Indoor/outdoor, %
		Indoor	Outdoor	
Penicillium	52	752	2379	32
		125	211	59
	46	28	37	76
	58	200	116	172
	50	18.0	5.2	346
	51	1325	58	2284
		726	112	648
	54	194	668	29
	55	3005	1692	178
	56	3.4	0.6	567
Cladosporium	57	205	2609	7.9
		224	2675	8.4
		5.3	2025	0.3
	58	122	585	21
	51	324	330	98
		258	290	89
	54	463	3097	15
	55	1573	5984	26
	56	0.9	4.4	20
Aspergillus	52	210	883	24
		64	71	90
	58	23	37	62
	51	7	4	175
		21	7	300
	54	53	204	26
	55	187	136	138
	56	0.2	0	∞
Hormodendron	50	3.7	18.8	20
	56	0.8	4.4	18
Mycelia sterilia	51	2	3	67
		5	3	167
	54	349	1171	30
	55	184	761	24
Mucor	52	149	0	∞
		35	0	∞
	58	9	10	90
	51	11	3	367
		15	2	750

Table A-6 (continued). INDOOR AND OUTDOOR CONCENTRATIONS OF SPECIFIC FUNGUS SPORES

Fungus	Reference	Mean concentration[a]		Indoor/outdoor, %
		Indoor	Outdoor	
Mucor (continued)	55	77	69	112
	56	0.3	0.1	300
Pullularia	58	34	164	21
	50	3.1	6.2	50
	54	25	588	4
	55	256	720	36
Yeasts	51	132 157	60 91	220 173
	55	513	1924	27
Alternaria	52	0 0	298 7	0 0
	58	5	44	11
	50	0.4	0.9	44
	51	4 2	10 6	40 33
	54	0	44	0
	55	46	234	20
Phoma	58	6	8	75
	50	0.1	0.5	20
	54	6	199	3
	55	22	108	20
Oospora	52	80 0	32 0	250
	51	0 0	1 1	0 0
	54	71	144	49
Botrytis	54	29	160	18
	55	53	328	16
	56	0.1	0.5	20
Epicoccum	54	9	152	6
	55	15	178	8
Sterile hyphae	52	7 0	91 0	8
Monilia	52	0 0	1 0	0 -
	54	9	21	43
	55	21	0	∞

Table A-6 (continued). INDOOR AND OUTDOOR CONCENTRATIONS OF SPECIFIC FUNGUS SPORES

Fungus	Reference	Mean concentration[a]		Indoor/outdoor, %
		Indoor	Outdoor	
Stemphylium	52	0 0	289 17	0 0
	55	24	66	36
Torulopsis	58	37	292	13
Torula	54	9	25	36
Rhodotorula	58	20	107	19
Sporotrichum	54	24	105	23
Candida	54	14	113	12
Fusarium	55	30	238	13
Aleurisma	55	31	48	65
Basidiomycetes	57	70 2.8	1276 1618	5.5[b] 0.2[c]
	55	18	48	38
Rhizopus	55	13	12	108
Ascomycetes	57	62.5	1294	4.8[b]

[a]See Note below for units of measure and study location.

[b]Hospital.

[c]Public building.

NOTE:

Reference	Measurement	Location/condition
52	Total colonies; 15-min exposure	Theater and two houses, Lexington, Kentucky. First measurement is summer; second winter
57	Grains/m^3; 24-hr concentration	Cardiff, England. First two measurements for hospitals; third for public building
58	Total colonies	Laboratory, Stockholm, Sweden
50	Colonies/sample; 15-min exposure	Homes, Copenhagen, Denmark
51	Colonies/m^3	First measurement for Madrid, Spain; second for Spanish coast
54	Total colonies, 10-min exposure	Houses, Cardiff, Wales
55	Total colonies	House and office, Stockholm, Sweden
56	Total colonies; 15-min exposure	Apartment, Copenhagen, Denmark
46	Colonies/sample	Houses, London, England

Table A-7. FUNGUS SPORE COMPOSITION OF INDOOR AND OUTDOOR SAMPLES IN EUROPEAN STUDIES

	Percent of total colonies															
													Spain[51]			
	Stockholm Sweden[58]		Stockholm Sweden[55]		Oerebro, Sweden[49]		Copenhagen, Denmark[50]		Copenhagen, Denmark[56]		Cardiff, Wales[54]		Madrid		Coast	
Fungus	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Penicillium	37.0	7.4	49.0	13.3	44	11	59	15	59.6	6.0	15.1	9.7	73.3	12.2	61.2	21.8
Cladosporium	22.6	37.2	25.6	47.1	-	-	-	-	15.8	44.0	35.9	45.2	17.9	69.0	21.7	56.4
Aspergillus	4.3	2.4	3.0	1.1	6.2	1.3	14	-	3.5	0	4.1	3.0	0.4	0.9	1.8	1.4
Hormodendron	-	-	-	-	28	68	12	53	14.0	44.0	-	-	-	-	-	-
Mycelia sterilia	-	-	3.0	6.0	-	-	-	-	-	-	27.1	17.1	0.1	0.6	0.4	0.6
Mucor	1.7	0.6	1.3	0.5	2.8	-	0.7	-	5.3	1.0	-	-	0.6	0.7	1.3	0.4
Pullularia	6.3	10.4	4.2	5.7	5.6	6.6	10	18	-	-	1.9	8.6	-	-	-	-
Yeasts	-	-	8.4	15.1	10	3.6	-	-	-	-	-	-	7.3	12.5	13.2	17.6
Alternaria	0.9	2.8	0.7	1.8	2.1	-	1.3	2.6	-	-	0	0.6	0.2	2.1	0.2	1.1
Phoma	1.1	0.5	0.4	0.8	-	-	0.3	1.5	-	-	0.5	2.9	-	-	-	-
Oospora	-	-	-	-	-	-	-	-	-	-	5.5	2.1	0	0.2	0	<0.1
Botrytis	-	-	0.9	2.6	-	1.5	-	-	1.8	5.0	2.2	2.3	-	-	-	-
Epicoccum	-	-	0.2	1.4	-	-	-	-	-	-	0.7	2.2	-	-	-	-
Monilia	-	-	0.3	0	-	-	-	-	-	-	0.7	0.3	-	-	-	-
Stemphylium	-	-	0.4	0.5	-	-	-	-	-	-	-	-	-	-	-	-
Torulopsis	6.8	18.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Torula	-	-	-	-	-	-	-	-	-	-	0.7	0.4	-	-	-	-
Rhodotorula	3.7	6.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sporotrichum	-	-	-	-	-	-	-	-	-	-	1.9	1.5	-	-	-	-
Candida	-	-	-	-	-	-	-	-	-	-	1.1	1.6	-	-	-	-
Fusarium	-	-	0.5	1.9	-	-	-	-	-	-	-	-	-	-	-	-
Aleurisma	-	-	0.5	0.4	-	-	-	-	-	-	-	-	-	-	-	-
Basidiomycetes	-	-	0.3	0.4	-	-	-	-	-	-	-	-	-	-	-	-
Rhizopus	-	-	0.2	0.1	-	-	-	-	-	-	-	-	-	-	-	-

Table A-8. FUNGUS SPORE COMPOSITION OF INDOOR AND OUTDOOR SAMPLES OF UNITED STATES STUDIES

	Percent of total colonies				
	Lexington, Kentucky[52]				Tucson, Arizona[53]
	Summer		Winter		
Fungus	Indoor	Outdoor	Indoor	Outdoor	Indoor and outdoor
Penicillium	67.2	59.8	55.8	69.0	7.1
Aspergillus	17.5	22.2	28.6	23.2	9.4
Hormodendron	-	-	-		13.6
Mycelia sterilia			-	-	3.1
Mucor	12.4	0	15.6	0	-
Pullularia	-		-		14.7
Alternaria	0	7.5	0	2.3	34
Oospora	6.7	0.8	0	0	-
Botryodiplodia	-		-	-	0.23
Sterile hyphae	0.6	2.3	0	0	-
Stemphylium	0	7.3	0	5.5	0.3
Candida	-	-		-	0.6
Fusarium	-		-	-	1.9
Rhizopus	-		-	-	0.9
Helminthosporium	-	-	-	-	8.2
Curvularia		-	-	-	2.0
Bisporia		-		-	1.4

Table A-9. RANGE AND OCCURRENCE OF FUNGUS SPORES IN INDOOR AND OUTDOOR SAMPLES, UNITED STATES AND EUROPEAN STUDIES[a]

Fungus	Range, percent of total colonies		Occurrence	
	Indoor	Outdoor	Indoor	Outdoor
Penicillium	15.1 to 73.3	6.0 to 69.0	10	10
Cladosporium	15.8 to 35.9	37.2 to 69.0	6	6
Aspergillus	0.4 to 28.6	0 to 23.2	10	8
Hormodendron	12 to 28	44.0 to 68	3	3
Mycelia sterilia	0.1 to 27.1	0.6 to 17.1	4	4
Mucor	0.6 to 15.6	0 to 1.0	9	5
Pullularia	1.9 to 10	5.7 to 18	5	5
Yeasts	7.3 to 13.2	3.6 to 17.6	4	4
Alternaria	0 to 2.1	0.6 to 7.5	6	8
Phoma	0.3 to 1.1	0.5 to 2.9	4	4
Oospora	0 to 6.7	0 to 2.1	2	4
Botrytis	0.9 to 2.2	1.5 to 5.0	3	4
Epicoccum	0.2 to 0.7	1.4 to 2.2	2	2
Sterile hyphae	0 to 0.6	0 to 2.3	2	2
Monilia	0.3 to 0.7	0 to 0.3	2	2
Stemphylium	0 to 0.4	0.5 to 7.3	1	3
Torulopsis	6.8	18.6	1	1
Torula	0.7	0.4	1	1
Rhodotorula	3.7	6.8	1	1
Sporotrichum	1.9	1.5	1	1
Candida	1.1	1.6	1	1
Fusarium	0.5	1.9	1	1
Aleurisma	0.5	0.4	1	1
Basidiomycetes	0.3	0.4	1	1
Rhizopus	0.2	0.1	1	1

[a]Does not include Tucson, Arizona, study shown in Table A-7b, since indoor and outdoor percentages were combined.

Table A-10. INDOOR AND OUTDOOR POLLEN CONCENTRATIONS

Location	Building type	Measurement	Concentration: Range, Indoor	Concentration: Range, Outdoor	Concentration: Mean, Indoor	Concentration: Mean, Outdoor	Indoor/outdoor, %	Remarks	
Philadelphia, Pennsylvania[43]	Houses	Grains/m^3	0 to 74	0 to 1100			6	Without air conditioner	
			0 to 28	0 to 1100			2	With air conditioner	
Philadelphia, Pennsylvania[59]	Houses			2 to 1100	11	205	5	Non-air-conditioned house	Test house
				2 to 1100	11	205	5	Air conditioner and air filter off	
				2 to 1100	2	205	1	Air filter off	
				2 to 1100	2	205	1	Air conditioner and air filter on	
Philadelphia, Pennsylvania[60]	Hospital		12.7 to 98.2	31.9 to 110	42.2	61.8	68	Windows open	No filter in air conditioner
			12.4 to 141	31.9 to 110	53.5	61.8	86	Windows open with air purifier	
			0.4 to 2.8	31.9 to 110	1.6	61.8	2	Air conditioned	
			0.4 to 2.8	31.9 to 110	1.0	61.8	2	Air conditioned with air purifier	
			11.9 to 68.3	60.0 to 272	33.8	119	28	Windows open	Standard filter in air conditioner
			26.8 to 82.0	60.0 to 272	57.9	119	49	Windows open with air purifier	
			0.7 to 2.6	60.0 to 272	1.6	119	1	Air conditioned	
			0.7 to 6.6	60.0 to 272	2.6	119	2	Air conditioned with air purifier	
Chicago, Illinois[61]	Hospital		6.6 to 392	14.4 to 914	92.8	262	36	Without air filter	
			1.3 to 23.6	14.4 to 914	7.9	262	3	With air filter	
Baltimore, Maryland[a]	School House		1 to 86	2 to 162	18	42	43	Day	
			1 to 37	5 to 251	8	67	12	Night	
Cardiff, Wales[57]	Hospital				6.7	496	1.4		
	Hospital				1.8	90.9	2.0		
	Public building				1.7	134.7	1.3		
Ann Arbor, Michigan[62]	Test building	Number/sample			6.6	37.4	18	Window closed, <8 mph wind	
					9.5	13.4	71	Window closed, >8 mph wind	
					9.1	21.9	42	Window open 1 inch, <8 mph wind	
					14.1	20.8	68	Window open 1 inch, >8 mph wind	
					17.7	52.8	34	Window open 3 inches, 3 to 5 mph wind	
					40.3	92.2	44	Window open 12 inches, 4 to 5 mph wind	
					13.5	34.3	39	Average	
Pittsburgh, Pennsylvania[63]	Hospital				144	1539	9.4	Without air filter	
					0	1539	0	With air filter	
Richmond, Virginia[64]	Hospital	Grains/day	7 to 407	71 to 1188			23	Non-air-conditioned room	
			0 to 2	71 to 1188			0.2	Air-conditioned room	
Chicago, Illinois[65]	Hospital	Grains/cm^2	0 to 23	10 to 350	6	133	4.5	With air filter	

[a]Unpublished data furnished by Mr. M. B. Rhyne.

Table A-11. INDOOR AND OUTDOOR CONCENTRATIONS OF BACTERIA

Type	Location	Building type	Measurement	Concentration: Range, Indoor	Concentration: Range, Outdoor	Concentration: Type, Indoor	Concentration: Type, Outdoor	Indoor outdoor, %	Remarks
Total bacteria	Osaka, Japan[12]	Apartment	Colonies/ sample, 5-min. exposure			27	16	169	October-November (48-hr culture)
						40	43	93	May
						16	21	76	June
						18	8	225	October-November (24-hr culture)
		House				57	4	1,425	October-November (24-hr culture)
						71	6	1,183	October-November (48-hr culture)
	Toyonaka, Japan[14]	Apartment	Bacteria/ sample, 5-min. exposure	5 to 126	7 to 147	35.0	43.0	82	Living room May
				8 to 134	7 to 147	44.0	43.0	102	Bedroom May
				2 to 68	1 to 118	13.0	21.0	62	Living room June
				4 to 78	1 to 118	18.0	21.0	86	Bedroom June
	Philadelphia, Pennsylvania[43]	Houses	Colonies/ sample, 15-min. exposure	0 to 45	0 to 60			75[a]	With air conditioner
				0 to 45	0 to 60			75[a]	Without air conditioner
Streptococci	New York, New York[66]	Offices	Number/ 100 ft^3			22	11	200	
		Schools				30	11	273	
Microbes (bacteria and spores)	New York, New York[66]	Offices	Number/ ft^3			87	52	167	Average for cultures at 20° and 37° C
		Schools				96	72	133	Cultures at 20° C

[a]Based on maximum values.

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